Stabilized Pulse Tube Cryocooler System with Infrared Lamp Heater for SQUID Magnetic Sensor

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Sensors
and
Materials

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A pulse tube cryocooler superconducting quantum interference device (SQUID) cooling system, in which temperature was controlled by an infrared source, was proposed. A high-Tc SQUID magnetometer was mounted and cooled by a coaxial pulse tube cryocooler. A light from a halogen lamp was guided by a quartz flexible bundle fiber and was introduced to the cold head. The output power of the lamp was controlled by a temperature controller in accordance with the cold-stage temperature. As a result, the flux noise of the SQUID output was not changed in the range of 1 to 1000 Hz regardless of the lamp power. The temperature could be controlled at 77 K with an accuracy of 0.03 K ± for a long time duration of more than 2 h. This demonstrated that the system can be applied to any application such as non destructive evaluation (NDE) systems.

1. Introduction

A high-Tc superconducting quantum interference device (SQUID)-based nondestructive evaluation (NDE) system is considered to be marketed.[1,2] For the operation of such a system in a factory, a liquid-nitrogen-free cryocooler is required because of the less requirement of daily maintenance. Recently, low-noise pulse tube cryocoolers (PTCs) have come out into the market.[3] However, in most of the systems a resistive heater is employed for the temperature control. Since the current associated with the resistive heater causes magnetic noise, an alternative method that results in no or less noise is desired. Although controlling the flow of the cooling medium of the refrigerator by adjusting a valve is one alternative method of controlling the temperature, it is hard to control the flow precisely in a matter of minutes. This method also has a problem in temperature stability. We propose the use of an infrared heat source for the temperature control system. In this paper, we will describe the design of the pulse tube cryocooler SQUID cooling system, in which temperature is controlled by an infrared source. The temperature stability and noise performances of the SQUID magnetometer mounted on the cryocooler will be discussed.

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2. System Design

   The whole system diagram is shown in Fig. 1. The system consists of three major components: a cryocooler, SQUID driving electronics and a temperature controller. We designed the system based on a coaxial pulse tube cryocooler (PR111 Aisin), which has a refrigerating capacity of 6 W at below 90 K. This coaxial-type PCT gives smaller mechanical vibration than a two-axial one. This cryocooler consists of a cold head, a rotary valve motor and a GM compressor. The cold head and valve motor are connected to each other by a 3-m-long copper tube. The cylindrical cryostat (90 × L230 mm), which maintains a high-vacuum condition around the cold head, is made of aluminum alloy. Since the compressor and rotary valve generate magnetic noise, they are separated from the cryostat and installed outside of a magnetically shielded room. The pressure oscillation frequency of the cryocooler generated by the motor-driven rotary valve is 4.5 Hz. The temperature of the cold head can be primarily controlled by the amount of helium gas flow. The cold head was extended by connecting a copper heat trasfer rod of ϕ 20 × 208nm to a region of magnetic noise generated by mechanical parts in the base of the cold head. The details of the temperature control system are shown in Fig. 2. A halogen lamp with a total reflection parabolic mirror was used as an infrared source. The light was guided by a
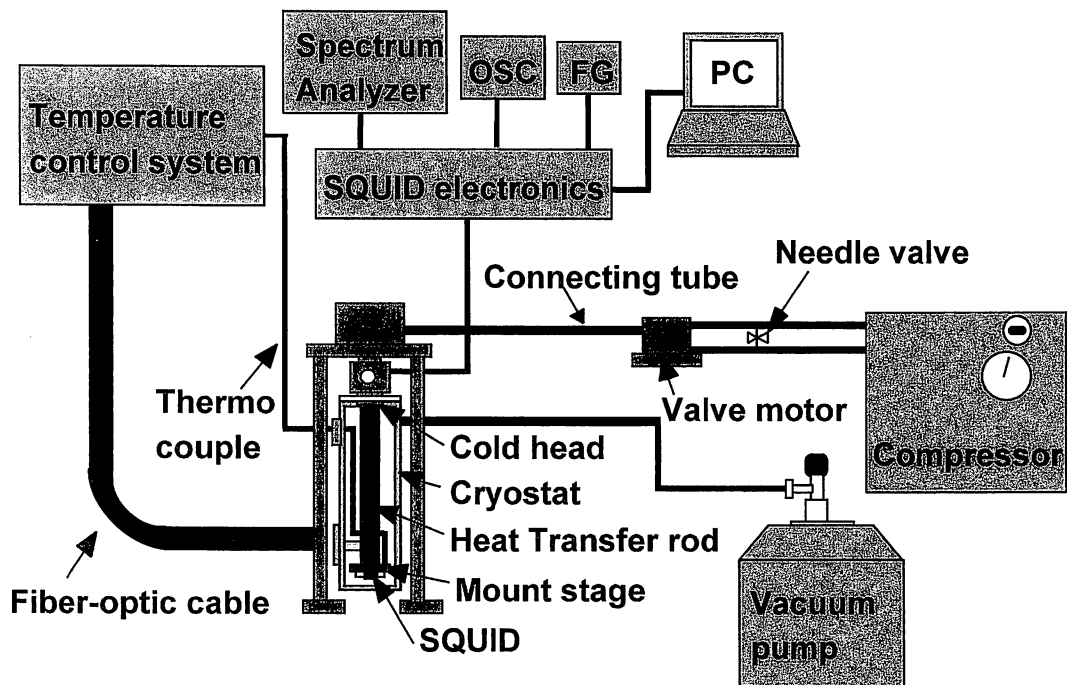

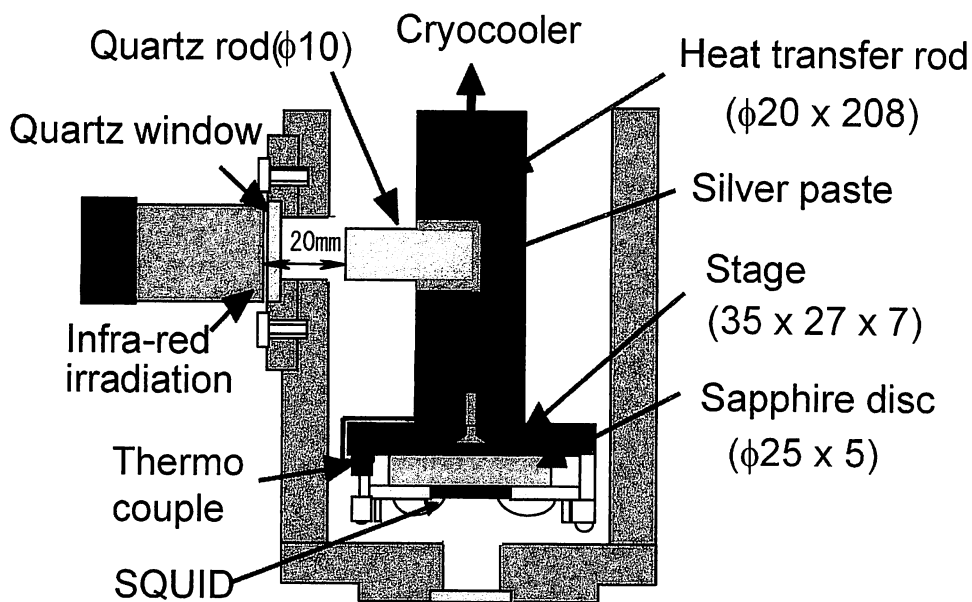Fig. 1.   System diagram of pulse tube cryocooler with infrared temperature controller.

Fig. 2. Details of temperature control system. The light was guided by a multicomponent bundle of optical fiber (3 m) and was introduced to the cold head.

multicomponent bundle of optical fibers (3 m) with a core diameter of 10 mm and was introduced to the cold head. We measured the transfer efficiency of the fiber using a power meter (TPM-300CE with PS-330, Gentec). As a result, the measured transfer efficiency was about 20% in the infrared wavelength range from 0.19 to 25 μm. The output power of the lamp was controlled by a LakeShore 331 temperature controller in accordance with the stage temperature measured by a gold-normal silver thermocouple. A close-up view of the cryostat is shown in Fig. 3. A short quartz rod with a diameter of 10 mm was connected to the heat transfer rod with silver paste. This rod was set near the view port with a spacing of 20 mm for thermal insulation. The optic fiber outlet was set outside of the view port so that the axis of the fiber core mates with that of the quartz rod inside the cryostat. A SQUID magnetometer was mounted on the copper stage via a sapphire disc with dimensions of ϕ 25 × 5 mm. The sapphire disc reduces the Johnson noise generated from the metallic copper stage. The SQUID is made of $Y_1Ba_2Cu_3O_{7-y}$ thin film.[4] The junctions utilized in the SQUID are of the bicrystal type. The washer size of the SQUID is about 5 × 4.5 mm^2 and the effective area is 0.05 mm^2. The SQUID was operated in a flux-locked loop with a flux modulation frequency of 256 kHz. The flux noise spectra of the SQUID was measured by a dynamic signal analyzer (36570A, Agilent Technologies).

We estimated the required energy to control the stage temperature of the cryocooler. The energy Q is calculated using the following equation,
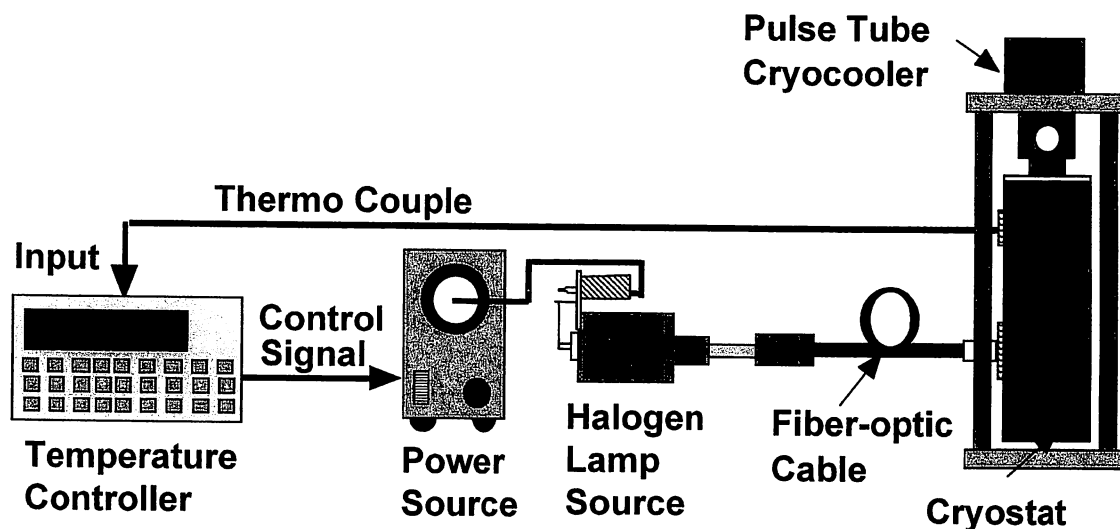
$$Q = VrT\Delta Cp, \tag{1}$$

Fig. 3. Close-up view of cold stage and infrared irradiation port.

where ρ, V, ΔT and Cp are the density of Cu, the volume of the transfer rod, the temperature difference and the specific heat at constant volume, respectively. The weight of the rod ρV is 560 g; ΔT is assumed to be 5 K and Cp at 70 K is 0.2 J/(gK).[5] From the calculation, we could find that a calorie expenditure of 560 J is required to increase the temperature of the transfer rod from 70 to 75 K. If the increasing time of 10 min is assumed, a heat flow of 0.9 W is at least required. This value can be afforded by our halogen source heating system.

3.   Measurement

3.1   *Temperature stability*

First, the temperature stability of the cold stage without feedback control was investigated. Figure 4 shows the results for a duration of 1.5 h. The flow control valve of the coolant gas was manually controlled so that the stage temperature was maintained at 77 K. However, the temperature could not be stabilized and moved up and down with a deviation of 0.5 K. If the temperature successfully reached the target temperature, it easily drifted. This means that it is hard to control the temperature by controlling the flow of the coolant for a long time.

Second, we utilized a feedback system using a halogen lamp irradiation. The coolant valve was adjusted so that the temperature of the cold stage becomes almost 1 K below 77 K. Then the feedback system was turned on. The time trace of the stage temperature is shown in Fig. 5(a). The temperature increased to reach the target temperature 77 K in about 20 min and was maintained for more than 2 h. A magnified scale view is shown in Fig. 5(b). It shows that the temperature is maintained at 77 K with a deviation of ±0.03 K. This
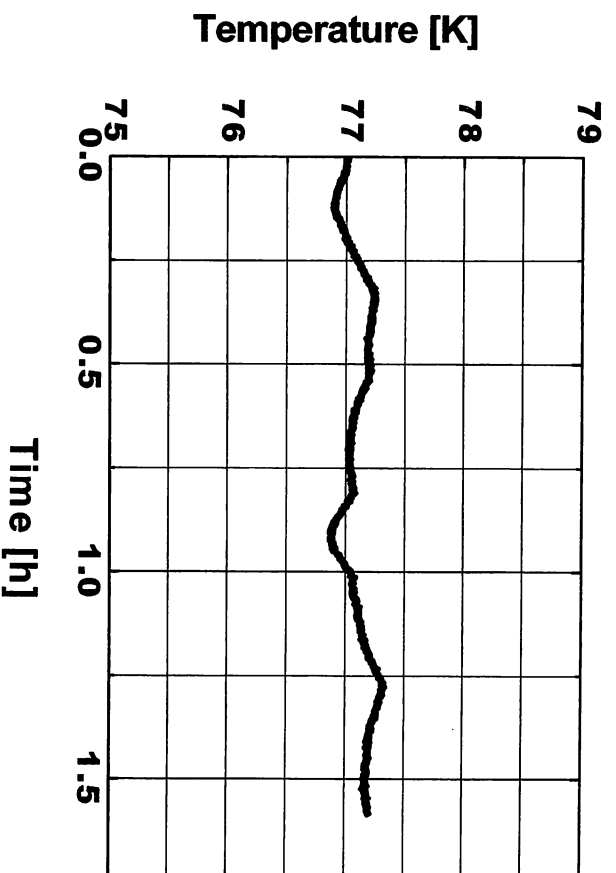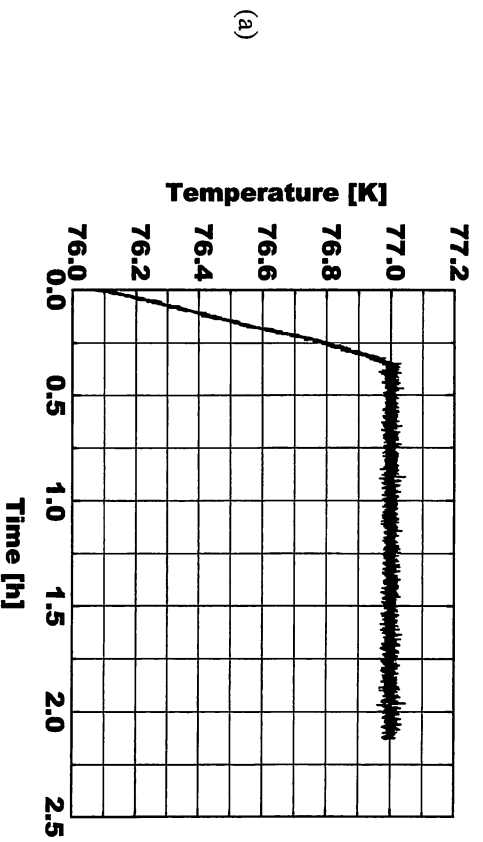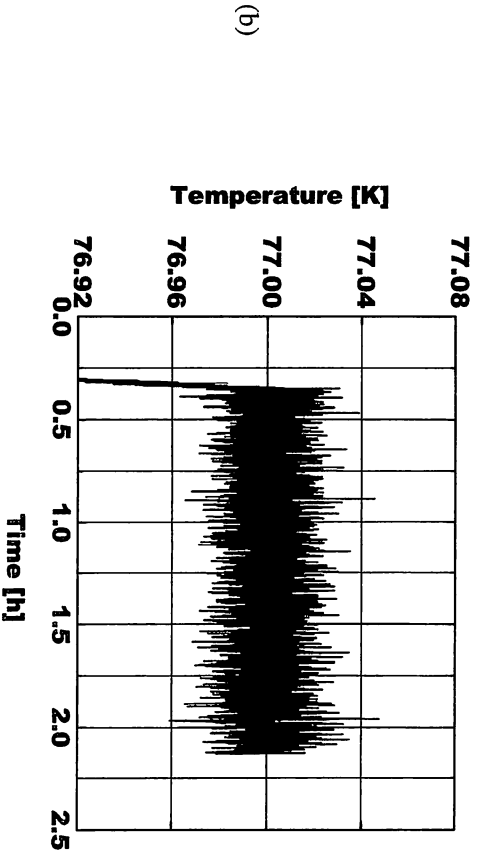
Fig. 4.   Time trace of temperature at cold stage.

(a)

(b)

Fig. 5.   The time trace of stage temperature for 2 h when infrared temperature controller was turned on. (a) Time trace for 2 h and (b) magnified scale view for the same time duration.

stability is high enough for high-Tc SQUID operation in most applications.

3.2 *System noise*

The flux noise spectra of the SQUID magnetometer mounted on the cold stage at various temperatures were measured. The temperature was controlled by adjusting the coolant gas flow; the temperature controller was not used here. The results are shown in Fig. 6. The flux noise of the SQUID measured in liquid nitrogen is also indicated for comparison. The temperature shown in the figure is the stage temperature. As indicated in the figure, the noise spectrum taken at 65 K is almost the same as that measured in liquid nitrogen, whose boiling temperature is 77 K. This means that the temperature of the SQUID mounted on the stage via a sapphire disc is 12 K higher than that of the cold stage. This difference comes from poor thermal conduction between the sapphire disc and the copper stage.

Then the flux noise spectra of the SQUID on the cold stage were measured with the feedback system using infrared irradiation. Before turning on the feedback system, the temperature of the cold stage was set at about 1 K below the target temperature of 63 K by adjusting the coolant flow. This stage temperature of 63 K corresponds to the SQUID temperature of 75 K. The flux noise spectra taken at the SQUID temperature of 75 K are shown in Fig. 7. One is a spectrum with feedback and the other is that without feedback. There is almost no difference between them. This means that the infrared heating feedback system does not make additional flux noise.
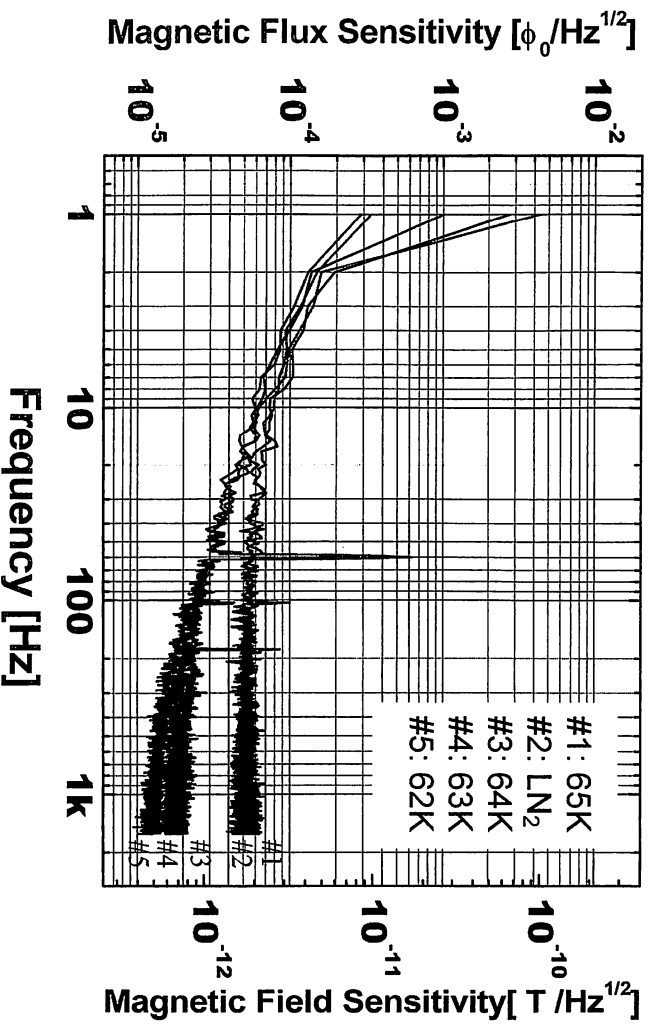

Fig. 6. Flux noise spectra of SQUID magnetometer mounted on cold stage at various temperatures.
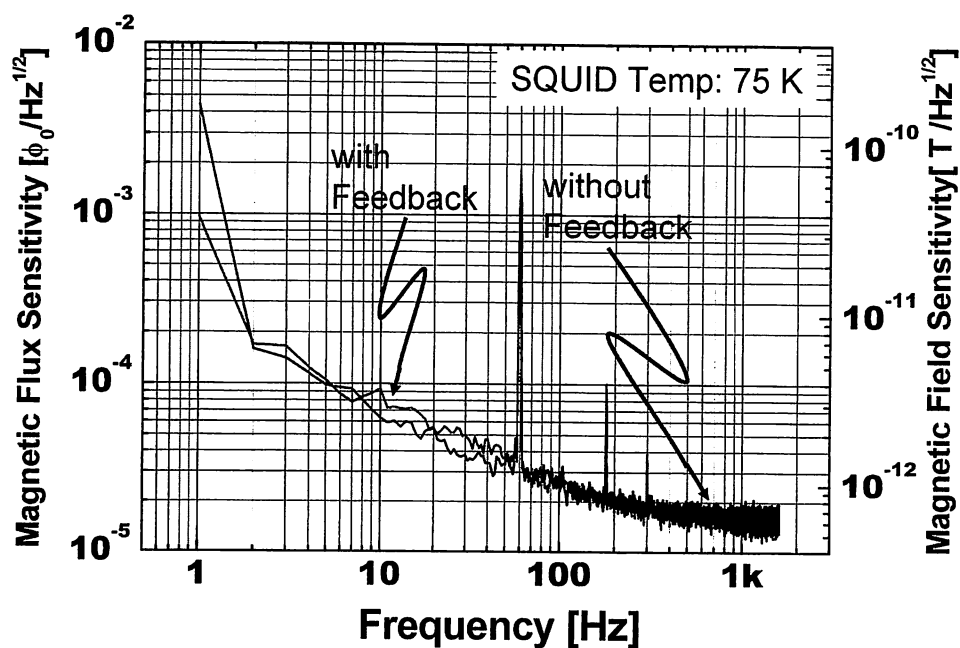
Fig. 7.   Flux noise spectra taken at SQUID temperature of 75 K.

4.   Summary

We have proposed a pulse tube cryocooler SQUID cooling system, in which temperature was controlled by infrared irradiation. The temperature could be controlled at 77 K with an accuracy of ±0.03 K for a long time duration of more than 2 h in this scheme. The infrared heating feedback system does not make additional flux noise.

References

1   S. Tanaka, M. Natsume, M. Uchida, N. Hotta, T. Matsuda, Z. Aspanut and Y. Hatsukade: Supercond. Sci. and Technol. **17** (2004) 620.
2   C. Carr, D. Graham, J. C. Macfarlane and B. Donaldson: IEEE Trans. Appl. Supercond. **13** (2003) 196.
3   Y. Hatsukade, A. Kosugi, K. Mori and S. Tanaka: Jpn. J. Appl. Phys. **43** (2004) 1488.
4   S. Tanaka, N. Tanaka, M. Natsume, M. Uchida, M. Oshita, Z. Aspanut, T. Eki and S. Yoshida: Supercond. Sci. and Technol. **16** (2003) 1536.
5   The Japan Society of Mechanical Engineers: Progress in Heat Transfer New Series ed. I. Tanazawa Vol. 3 (Yokendo, Tokyo, 2000) p. 275.