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Pulse tube cryocooler SQUID cooling system involving an infrared temperature controller cooled by a cryocooler

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Abstract

We propose a pulse tube cryocooler SQUID cooling system, which temperature was controlled by an infrared source. A high-T_c 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 1–1000 Hz regardless of the lamp power. The temperature could be controlled at 77 K with accuracy of ±0.03 K for long time duration more than 2 h. This demonstrated that the system can be applied to any applications such as NDE systems.

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Keywords: SQUID; Temperature control; Infrared; Cryocooler

1. Introduction

High-T_c SQUID based NDE system is considered to be marketed [1,2]. For the operation of such a system in a factory, liquid nitrogen-free-cryocooler is required because of the less daily maintenance. Recently, low noise pulse tube cryocooler (PTC) has come to the market [3]. However, in the most of the system a resistive heater is employed for the temperature control. Since the current associated with the resistive heater causes magnetic noise, an alternative noise less method is desired. Although controlling the flow of the cooling medium of the refrigerator by adjusting a valve is one alternative method to control the temperature, it is hard to control precisely in a matter

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of minutes. It has also a problem in a stability of the temperature. We propose 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, which temperature is controlled by an infrared source. The temperature stability and the noise performances of the SQUID magnetometer mounted on the cryocooler will be discussed.

2. System design

The whole system diagram is shown in Fig. 1. It consists of three major components: a cryocooler, SQUID driving electronics and a temperature controller. We designed the system based on a co-axial pulse tube cryocooler (PR111 Aisin), which refrigerating capacity is 6 W below 90 K. This coaxial type PCT gives smaller mechanical vibration than two-axial one. This cryocooler consists of a cold head, a rotary valve motor and a GM compressor. The cold head and the valve motor are connected each other by a 3 m long copper connecting tube. The cylindrical cryostat (ϕ90 mm × L230 mm), which keeps high vacuum condition around the cold head, was made of aluminum alloy. Since the compressor and the rotary valve generate magnetic noises, they are separated from the cryostat and installed out 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 transfer rod of ϕ20 × 208 mm to prevent magnetic noise generated by parts in the base of the cold head. The detail of the temperature control system is 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 multi component bundle optical fiber (3 m) with core diameter of 10 mm and was introduced to the cold head. We measured the transfer efficiency of the fiber by power meter (TPM-300CE with PS-330, gentec). As a result, it was about 20% at the infrared wavelength. 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. Close up view of the cryostat is shown in Fig. 3. A short quartz rod with diameter of ϕ10 mm was connected to the heat transfer rod with silver paste. This rod was set near the view port with spacing of 20 mm for thermal insulation. The optic fiber outlet was set outside of the view

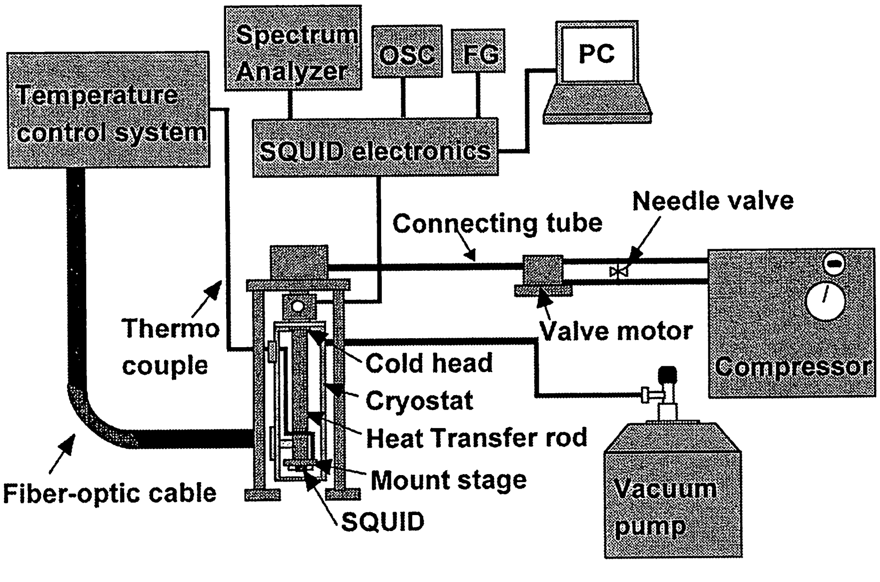

Fig. 1. System diagram of pulse tube cryocooler with infrared temperature controller. It consists of three major components: a cryocooler, SQUID driving electronics and a temperature controller.

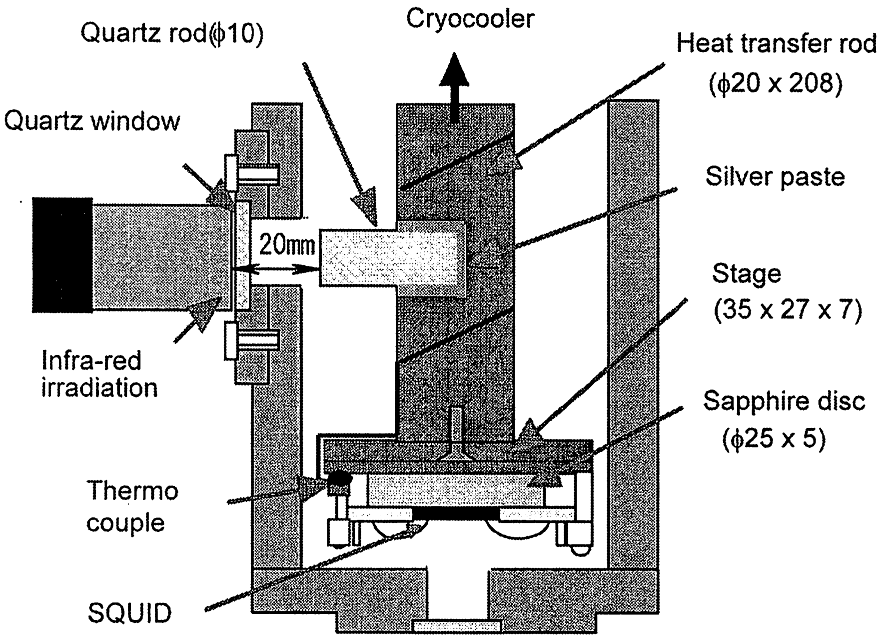

Fig. 2. Detail of the temperature control system. The light was guided by a multi component bundle optical fiber (3 m) and was introduced to the cold head.

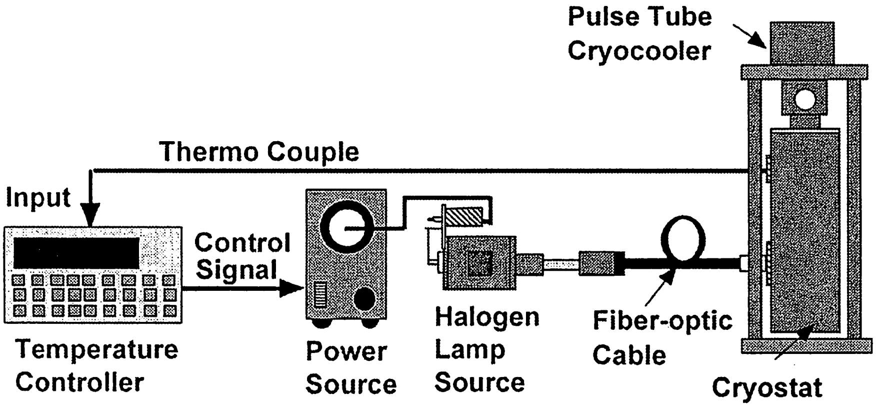

Fig. 3. Close up view of cold stage and infrared irradiation port. A short quartz rod was connected to the heat transfer rod. This rod was set near the view port with spacing for thermal insulation.

port so that the axis of the fiber core mate with that of the quartz rod inside the cryostat. A SQUID magnetometer was mounted on the copper stage via a sapphire disc with dimension of (ϕ25 mm × 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 bi-crystal type. The washer size of the SQUID is about $5 \times 4.5\,\mathrm{mm}^2$ and the effective area is $0.05\,\mathrm{mm}^2$. 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).

3. Estimation of energy

We estimated the required energy to control the stage temperature of the cryocooler. The energy Q is calculated by the following Eq. (1):

$$Q = \rho V \Delta T C_p \tag{1}$$

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

4. Measurement

4.1. Temperature stability

First, temperature stability of the cold stage without feedback control was investigated. Fig. 4 shows the results for the 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 the deviation of 0.5 K. Even if the temperature successfully achieved at the target temperature, it easily drifted. This means that it is hard to control the temperature by controlling the follow of the coolant for long time.

Second, we utilized 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 the 77 K and then the feedback system was turned on. The time trace of the stage temperature is shown in Fig. 5(a). The temperature increased at the target temperature 77 K in about 20 min and was maintained for more than 2 h. The magnified scale is shown in Fig. 5(b). It shows that the temperature is maintained at 77.00 K with deviation of ±0.03 K. This stability is high enough for high-T_c SQUID operation in most of the applications.

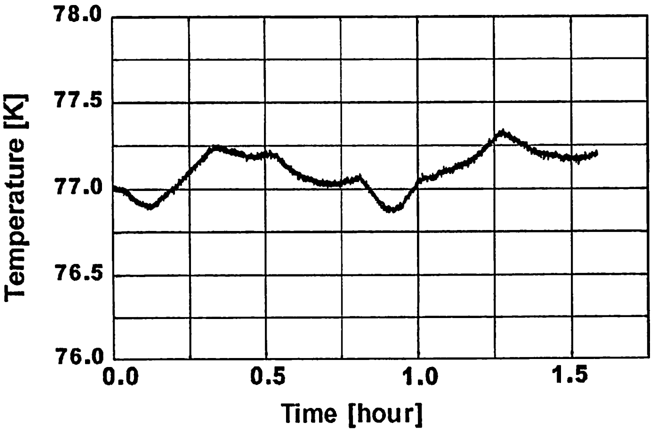

Fig. 4. Time trace of temperature at cold stage. The temperature controller was not used in this case and the temperature was controlled by adjusting only a coolant flow valve.

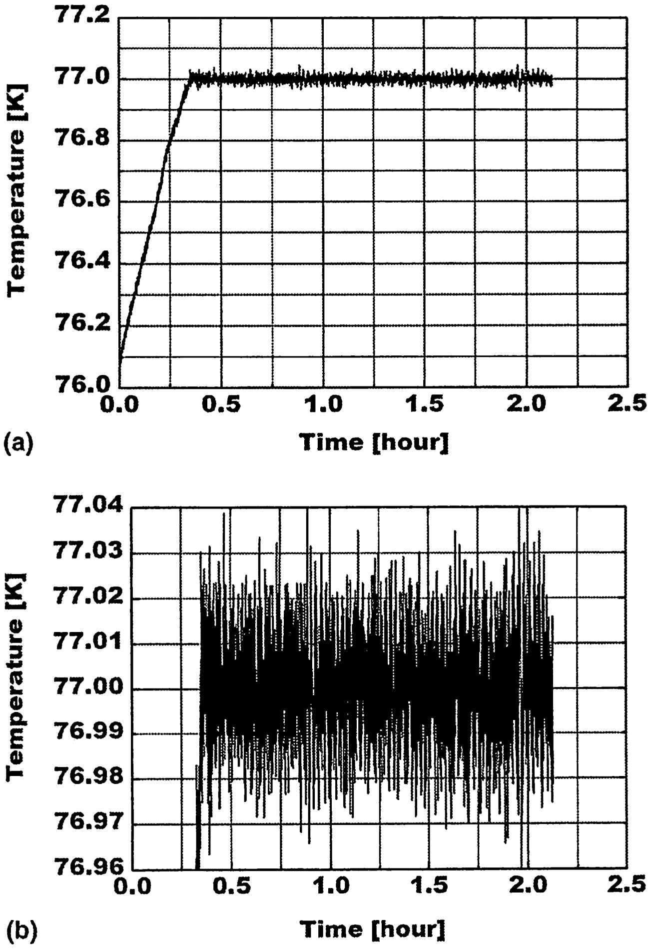

Fig. 5. The time trace of the stage temperature for 2 h when the infrared temperature controller was turned on. (a): Time trace for 2 h and (b) magnified scale view for the same time duration. The temperature increased at the target temperature 77 K in about 20 min and was maintained for more than 2 h.

4.2. System noise

Flux noise spectra of the SQUID magnetometer mounted on the cold stage at various temperatures

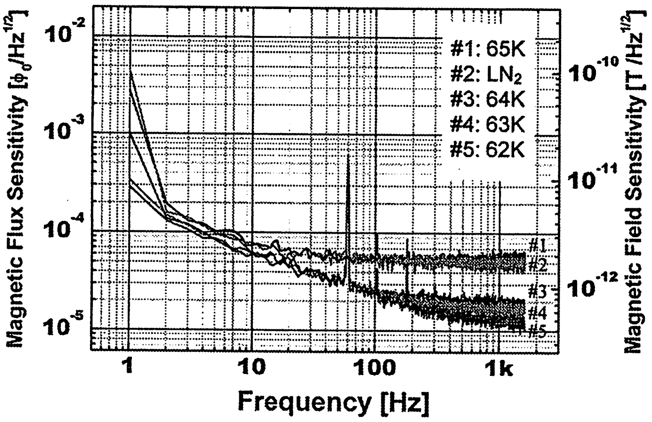

Fig. 6. Flux noise spectra of the SQUID magnetometer mounted on the cold stage at various temperatures. The temperature was controlled by adjusting the coolant gas flow; the temperature controller was not used here. The spectra of the SQUID measured in liquid nitrogen are also indicated for the comparison.

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 the 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, which 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 form 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 the infrared irradiation. Before turning on the feedback, 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 SQUID temperature of 75 K are shown in Fig. 7. One is spectrum with the feedback and the other is that without the feedback. There is almost no difference between them. This means that the operation of the infrared heating feedback system does not make additional flux noise.

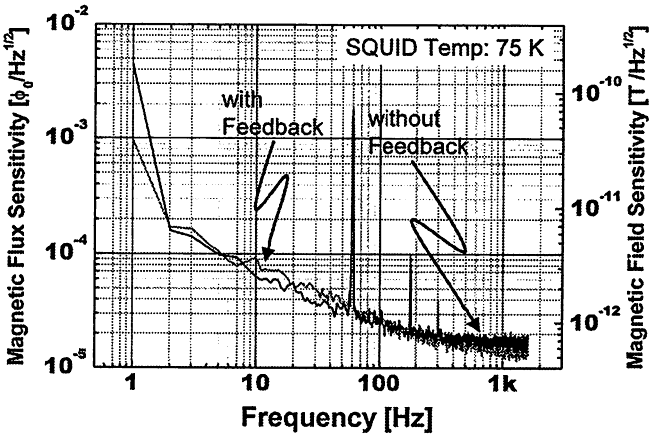

Fig. 7. The flux noise spectra taken at SQUID temperature of 75 K. One is spectrum with the feedback and the other is that without the feedback.

5. Summary

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

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