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► To cite this version:

R.J. Soulen, T.F. Finnegan. A microwave resistive squid for noise thermometry. *Revue de Physique Appliquée*, 1974, 9 (1), pp.305-307. 10.1051/rphysap:0197400901030500 . jpa-00243763

HAL Id: jpa-00243763

<https://hal.science/jpa-00243763>

Submitted on 1 Jan 1974

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A MICROWAVE RESISTIVE SQUID FOR NOISE THERMOMETRY

R. J. SOULEN and T. F. FINNEGAN

Institute for Basic Standards, National Bureau of Standards
Washington, DC 20234, USA

Résumé. — Un SQUID travaillant à 10 GHz apporte une nette amélioration du rapport signal sur bruit par rapport aux dispositifs fonctionnant à 30 MHz. Cet article montre comment une telle amélioration peut conduire à des mesures de température plus rapides. On décrit les performances d'un SQUID résistif travaillant à 10 GHz. La possibilité de réaliser un tel système est donc clairement établie.

Abstract. — A SQUID magnetometer has been shown to work at 10 GHz with a significant enhancement of signal-to-noise over 30 MHz devices. This article describes how such enhancement could lead to faster determinations of absolute temperature using a resistive SQUID, i. e., a noise thermometer. A prototype 10 GHz resistive SQUID is described and its performance evaluated. The feasibility of using a 10 GHz system is clearly established.

1. Introduction. — In principle, a resistor may be used as a thermometer, since the voltage fluctuations (i. e., noise) across it are related to its absolute temperature by the equation [1]

$$\langle V_n^2 \rangle = \int_0^\infty 4 kRT df, \quad (1)$$

where k is the Boltzmann constant ; R , the resistance ; T , the absolute temperature ; and f , the frequency. Conventional noise thermometers based on this principle were usually limited to 3 % measurements of T and to temperatures above 5 K owing to thermal noise in the room temperature amplifiers used to measure the voltage fluctuations. In 1967, Kamper [2] suggested a novel technique for noise thermometry using a Josephson junction which permits high accuracy measurements at very low temperatures.

The scheme consists of connecting a resistor in parallel with a point-contact Josephson junction. The instantaneous noise voltage, $V_n(t)$, is converted by the junction into an ac signal of frequency f , where the conversion factor is determined by the Josephson equation [3]

$$hf = 2eV. \quad (2)$$

Here V is the total voltage across the junction ; e , the electronic charge ; and h , Planck's constant. This ac signal, generally in the audiofrequency range, is used to amplitude modulate a radiofrequency signal injected into the circuit. After radiofrequency amplification and demodulation at room temperature, the audio-frequency output directly reflects or represents the noise voltage in the cryostat. Another feature of this noise thermometer (it is also referred to as a resistive

SQUID) is that the broadband noise voltage fluctuations are compressed by the Josephson junction into frequency fluctuations limited to a bandwidth given by [4]

$$df = \frac{4\pi kRT}{\varphi_0^2}, \quad (3)$$

where φ_0 is the flux quantum. A more complete analysis [5] shows that the output power of the device exhibits a Lorentzian line shape with a full width at half maximum given by eq. (3). Thus, one method for determining absolute temperature with this device is to plot the line shape and use eq. (3). Such a technique was originally used by Silver *et al.* [6] to test the noise thermometer to 10 % in the range 1 K to 8 K.

Another technique capable of higher precision [4] is to drive a frequency counter with the audiofrequency output of the system and to calculate the variance from the equation

$$\sigma^2 = \sum_{i=1}^N \frac{(f_i - f_{i+1})^2}{2N}, \quad (4)$$

where f_i is a given frequency count from the counter, and N is the total number of frequency counts taken. When the frequency fluctuations are caused by a resistor (i. e., Johnson noise), the variance, σ , is related to T by [4]

$$\sigma^2 = \frac{2kRT}{\varphi_0^2 \tau} \quad (5)$$

where τ is the gate time of the frequency counter. The resistance can be obtained in the same experiment by

measuring the dc current sent into the resistor, the average audiofrequency, and using eq. (2). Thus, once the variance is calculated from eq. (4), the absolute temperature is easily obtained.

In a system now in use at the National Bureau of Standards [7], [8], the frequency counter is « interfaced » to an on-line computer which has been programmed to calculate the variance of the frequency counts. The accuracy of the temperature measurement is determined by the standard statistical law, thus

$$\frac{\Delta T}{T} = \left(\frac{2}{N}\right)^{1/2}. \quad (6)$$

A 1 % measurement of T requires that $N = 2 \times 10^4$, and a 0.1 % measurement requires $N = 2 \times 10^6$. Such a large number of data points puts a premium on rapid data acquisition. The frequency counter, interface, and computer are capable of accepting frequency counts and calculating the variance at a rate of 10^4 frequency counts per second, i. e., with $\tau = 10^{-4}$ s. At present, the total system is limited to data acquisition rates ≤ 10 counts/s for reasons explained below which are associated with operation of the resistive SQUID at 30 MHz.

We have observed that the bandwidth of the frequency fluctuations (given by eq. (3)) must satisfy the approximate criterion,

$$df \geq \frac{100}{\tau} \quad (7)$$

in order to prevent significant loss of information. Thus, if we wish to collect data at a rate of 10^4 counts/s with a gate time of 10^{-4} s, the bandwidth must exceed 1 MHz. Inspection of eq. (3) shows that at 1 K, the resistor must have a value of $2.5 \times 10^{-2} \Omega$. The first problem, then, stems from a difficulty in constructing such a large resistance and still satisfying several other criteria necessary for successful operation of the resistive SQUID at 30 MHz. In particular, poor coupling of 30 MHz into the SQUID requires a circuit Q of 100, which is difficult to achieve with a $2.5 \times 10^{-2} \Omega$ resistance. There is an even more serious factor to consider; i. e., the post-detection bandwidth of the SQUID amplifier must exceed df . For the case cited above, we would conservatively require a post-detection bandwidth of 2 MHz. Unfortunately, with a 30 MHz SQUID amplifier, a post-detection bandwidth of 2 MHz would yield such a poor input signal to the frequency counter that amplifier noise would trigger the counter and cause incorrect readings. In practice, a power signal-to-noise ratio of 14 dB is usually needed to prevent incorrect countings and requires a 5 kHz post-detection bandwidth for a 30 MHz SQUID amplifier. Thus, from eq. (7), we conclude that a 30 MHz system is limited to data acquisition rates as fast as 10/s.

One method to improve the signal-to-noise ratio and to permit larger post-detection bandwidths is to

operate the resistive SQUID at a higher pump frequency [9]. Kamper and Simmonds [10] have recently built a 10 GHz SQUID magnetometer, and it was our expectation that such a magnetometer could easily be converted into a noise thermometer by the appropriate insertion of a resistive section. We would expect the enhancement of the signal at 10 GHz compared to that from a 30 MHz radiofrequency system to be approximately 25 dB, which should permit a post-detection bandwidth of 1.5 MHz and still maintain a 14 dB signal-to-noise ratio. An added benefit of working at 10 GHz is that the microwave field couples well to the Josephson junction so that a high Q circuit is not necessary [10]. Thus, it should be easier to use high resistance SQUIDS ($\geq 10^{-3} \Omega$) at this frequency.

2. 10 GHz resistive SQUID. — The 10 GHz resistive SQUID we tested is shown in figure 1. It consists of a section of X-band waveguide reduced to 0.25 mm in the E direction to give a characteristic impedance of 10Ω in order to match it to the impedance of the Josephson junction. The junction is formed by rotating the adjustment lever attached to a flat niobium screw until it gently touches the sharpened end of a fixed niobium screw. The junction is placed a distance of

FIG. 1. — 10 GHz resistive SQUID. Upper drawing shows side view of the device; the lower figure shows the top view.

$\lambda/4$ from the shorted end of the guide where the electric field is a maximum. The interior of the guide is lined with a superconducting material (Babbitt metal). A circular groove has been machined in the upper half of the guide, thus placing a section of brass resistor ($\sim 3 \mu\Omega$) in parallel with the junction. Direct current is passed through the resistor by connecting a coaxial line leading from room temperature to two solder connections shown in figure 1.

The resistive SQUID is matched to the $50\ \Omega$ X-band waveguide which leads to room temperature via a 10 cm section of tapered waveguide. The electronic system used to observe the signal from the SQUID is shown in figure 2. Approximately 5×10^{-11} W was coupled to the resistive SQUID through a 3 dB directional coupler. The signal reflected from the SQUID passes through the directional coupler to a superhetrodyne receiver. The output of the intermediate frequency amplifier near 30 MHz was observed with a spectrum analyzer; the video output was displayed on an oscilloscope.

FIG. 2. — Block diagram of the electronics used to observe quantum oscillations of the 10 GHz resistive SQUID. Two isolators (not shown) were connected between the receiver and the directional coupler.

3. Results. — The resistive SQUID shown in figure 1 was immersed in liquid He^4 at 4.2 K. The 30 MHz output is shown in figure 3. The signal at the center was proportional to the 10 GHz signal reflected from the cryostat which, in this instance, was approximately 5×10^{-11} W. The resistor was biased at 2×10^{-9} V with a current at 0.66 mA. This voltage (see eq. (2)) caused the junction to oscillate at 1 MHz. This oscillation produced a 20 % amplitude modulation of the 10 GHz signal, giving rise to the two sidebands in figure 3. By varying the dc voltage, we found that the frequency of the sidebands could be

FIG. 3. — Spectrum analysis of the 30 MHz output of the resistive SQUID at 4.2 K.

Vertical scale : IF output, uncalibrated.
Horizontal scale : 500 kHz per division.

continuously adjusted between 0 and 5 MHz; the upper limit was determined by the bandwidth of the intermediate frequency amplifier. We observed quantum oscillations over a power range from 10^{-11} to 10^{-9} W, depending on the adjustment of the point contact. The optimum power for obtaining the best signal-to-noise (S/N) for the video output was found to be 5×10^{-11} W. For this power level and a post-detection bandwidth of 100 kHz, the power S/N was determined to be ~ 28 dB. Finally, at power levels near 10^{-10} W we did observe more complicated spectra with additional sidebands corresponding to higher harmonics of the fundamental frequency given in eq. (2).

4. Conclusions. — A power S/N enhancement of 28 dB has been achieved in a resistive SQUID by increasing the pump frequency from 30 MHz to 10 GHz. In order to take full advantage of this demonstrated enhancement, it will be necessary to increase the bias resistance of the SQUID. These experiments are now in progress.

Acknowledgments. — The authors are indebted to R. A. Kamper for many helpful discussions and for making available to us a noise thermometer for preliminary tests.

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