Properties of a High-T_c dc SQUID Radiofrequency Amplifier

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***Abstract*—We present an experimental investigation of a radiofrequency amplifier based on a bicrystal high-T_c dc SQUID designed for the frequency range 500–3000 MHz. The SQUID input coil comprises only one layer of a normal metal forming open-ended microstrip line. Both dc and microwave properties were investigated and analyzed. Maximum power gain was found to be 16 dB at 520 MHz for a SQUID with 8 turn input coil.**

***Index Terms*—High-temperature superconductors, microwave measurements, SQUIDS.**

I. Introduction

THE first practical radiofrequency amplifier based on a low-T_c Nb dc SQUID was demonstrated more than fifteen years ago [1]. Since then, several approaches have been developed in order to achieve high power gain and low noise temperature [2], [3]. In spite of the ultimate noise performance, such amplifiers have various disadvantages such as low dynamic range, high intermodulation products mainly due to the limited SQUID voltage-to-flux transfer function, and absence of feedback. Recently, a new design for a low-T_c Nb SQUID amplifier with a microstrip input coil was suggested [4]. This design reduced the SQUID loop inductance and the capacitance between the input circuit and the loop. Such a design with a normal metal coil replacing superconducting coil is very attractive for high-T_c superconductor technology where fabrication of multilayer superconducting structures is complicated.

In our previous work [5], [6] we developed a technological approach for high-T_c dc SQUID radiofrequency amplifier based on bicrystal dc SQUID with normal metal input coil separated by an amorphous dielectric layer from the SQUID washer. The purpose of the present work is to analyze the margins of the high-T_c dc SQUID with a normal metal input coil used as a radiofrequency amplifier.

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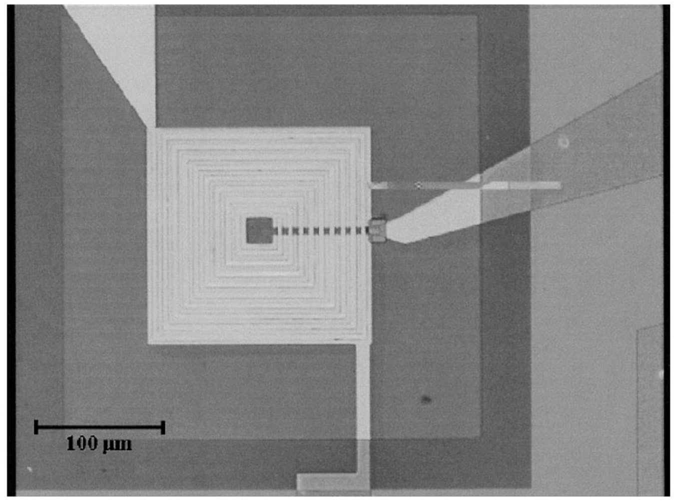

Fig. 1. Microphotograph of the high-T_c dc SQUID amplifier on YSZ bicrystal substrate with 30° misorientation angle.

II. Device Design and Fabrication

A detailed description of our technological process can be found elsewhere [5].

A 180 nm YBCO film was deposited by conventional laser ablation with an excimer KrF mixture laser ($\lambda = 248$ nm), buffer oxygen pressure 0.3 mbar and substrate temperature $T = 745°$C. A thin gold film was deposited both by e-beam evaporation and magnetron sputtering. SQUID structure was patterned with optical photolithography and ion-beam etching in Ar^+ ions with energy 250 eV and current density 0.2 mA/cm^2. The input coil was patterned by a lift-off. A microphotograph of the SQUID amplifier on a bicrystal ZrO_2 substrate with 30° misorientation angle is shown in Fig. 1.

III. Background

A. Input Coil Design

The choice of the input coil parameters is contradictory. In order to achieve the highest power gain it is necessary to use coils with a large turn number to increase the mutual inductance between the coil and SQUID washer. In our previous work we analyzed the input coil in terms of a band pass filter. One important outcome was that the coil length significantly limits the operational frequency range of the amplifier. On the other hand, the input coil size is correlated with SQUID inductance,

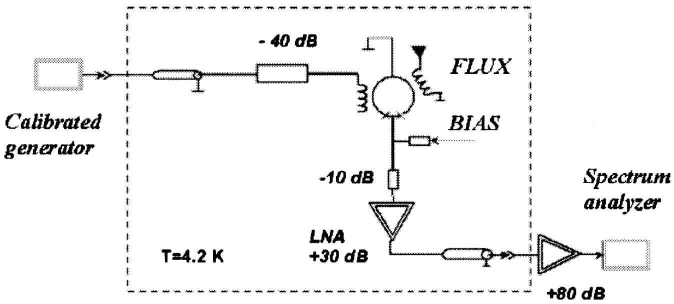

Fig. 2. Configuration of the experimental setup for power gain measurements.

which is constrained by SQUID performance considerations. The best solution is to adjust the coil line width in order to vary its length keeping the total SQUID inductance fixed near the optimal value.

B. Optimal SQUID Parameters

The SQUID inductance is not the only the factor affecting on the SQUID amplifier performance. In order to obtain better microwave matching the dynamic resistance at the optimal bias point should be close to 50 Ohm for both the amplifier input and output. The SQUID inductance should coincide with the optimal value for a given I_C. Thus, the overall performance is determined by of the $I_C R_N$ value, where R_N is the normal resistance of the Josephson junction.

For high-T_C SQUIDs at 4.2 K the typical $I_C R_N$ is about 1–2 mV depending on the Josephson junction quality and misorientation angle. According to this, the critical current I_c should not exceed 50–70 μA, SQUID total inductance $L_S \approx$ 50–100 pH.

IV. Experimental Results

The experimental setup is shown in Fig. 2. For power gain measurements a calibrated generator was used. The small signal (typically -110 dBm referred to SQUID input) from generator was directly coupled to the input coil through dc block and -40 dB cold attenuator. There filters were used to decrease the noise level from room temperature electronics to avoid SQUID saturation. First stage low noise amplifier with $+30$ dB gain was installed on the cold stage. Two room-temperature amplifiers with total gain $+80$ dB were used to bring the signal up to the network or spectrum analyzer. Thus, the overall amplifiers gain was $+110$ dB. The SQUID was installed inside superconducting and μ-metal shields.

Before SQUIDs were tested, the full circuit amplitude-to-frequency response was investigated in the range 200–3000 MHz (Fig. 3) corresponding to the cold LNA bandwidth. A blank YSZ substrate was used instead of the SQUID chip in this measurement. The response is relatively flat with a small gap at 500 MHz, presumably from the cold LNA.

A SQUID made on YSZ bicrystal substrate with 30° misorientation angle was investigated in detail. The input coil has 8 turns and 5 μm linewidth. The insulator thickness is 170 nm. The SQUID has critical current $I_C = 50$ μA and normal resistance $R_N = 10$ Ω, giving the $I_C R_N = 0.5$ mV.

To measure the power gain we used a spectrum analyzer to observe the SQUID response directly. The bias point was adjusted for a maximum voltage-to-flux response (150 μV/Φ_0); $V_{\mathrm{BIAS}} \approx 200$ μV corresponding to a Josephson frequency of 100 GHz.

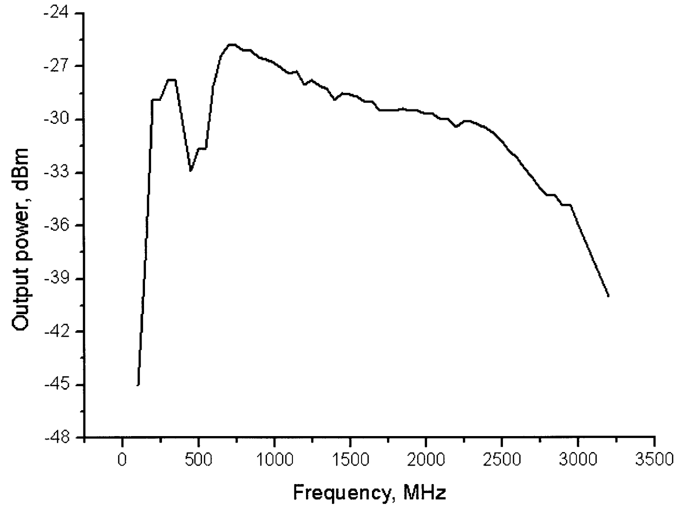

Fig. 3. Amplitude-frequency response of the comprehensive measurement circuit for blank YSZ substrate. The signal power is -50 dBm referred to the generator output. The total microwave losses through the circuit are -13 dB.

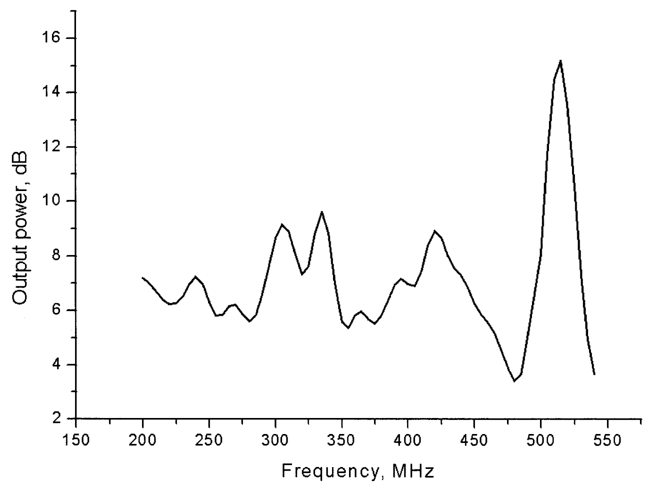

Fig. 4. Power gain of high-T_c dc SQUID amplifier with $N = 8$.

When the SQUID was introduced in the microwave circuit the total losses increased up to 25 dB. The origin of the additional losses is apparently inside the SQUID structure. In the present investigation we have not made any special efforts to reveal the loss mechanism.

The result of the power gain measurements in the particular 200–600 MHz range is shown in Fig. 4. This dependence was obtained by subtraction of the output signal level observed at different values of the external magnetic flux $\Phi_E = n\Phi_0/2$ and $(n \pm 1/4)\Phi_0$. The maximum power gain 16 ± 1 dB was observed at 520 MHz. Above 550 MHz there was no significant gain.

V. Discussion

In this paper we presented an investigation of a high-T_c dc SQUID amplifier with a microstrip normal metal input coil. In spite that the SQUID did not have ultimate performance,

$I_C R_N = 500\ \mu$V, we observed significant power gain of 16 dB at 520 MHz.

With respect to our previous results with smaller coils (4–5 turns), the resonant frequency became lower but the power gain increased. The mentioned in [7], this is mainly connected with the stray capacitance and inductance of the input coil.

It is more important to understand the reason for high insertion losses in the SQUID. This can be due to the normal metal input coil. Additionally, we did not specially examine the high frequency behavior of the amorphous dielectric used between the input coil and SQUID washer.

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