Electrical Characteristics of Thin-Film $Ba_2YCu_3O_7$ Superconducting Ring Resonators

P. A. Polakos, C. E. Rice, M. V. Schneider, and R. Trambarulo

Abstract—**The development of high-temperature superconducting thin films has opened up new opportunities for microstrip applications to exploit the low-loss properties of these films. It is reported that the microwave performance of superconducting microstrip ring resonators between 2 and 22 GHz for which both microstrip and ground plane were fabricated from $Ba_2YCu_3O_7$ films deposited on both sides of the same $LaAlO_3$ substrate. At 9.5 GHz, resonances were observed with intrinsic Q's of ~7500 at 75 K and ~20,000 at 25 K. The 75 K value represents an improvement of a factor 20 over Au.**

I. Introduction

The low-loss, low-dispersion properties of high temperature superconductors, in particular $Ba_2YCu_3O_7$, offer great promise for application in passive microwave circuits. Surface resistance measurements yield steadily decreasing values as the quality of material improves. Recent measurements on patterned films at 77 K have shown that an improvement of a factor 10 over conventional films at 10 GHz is achievable [1], although extrapolation of data from higher frequency suggests a factor 100 improvement is possible [2], [3]. The availability of low-loss epitaxial substrates [4] and the ability to deposit high-quality thin films on both sides now permit the fabrication of extremely low-loss circuits having true microstrip geometry (i.e., without an intervening air gap between the strip conductor and the ground-plane). We have fabricated superconducting ring resonators with this geometry to study the characteristics of superconducting microstrip with this technology. In this letter we describe the resonators and discuss the principal features of their response.

II. Film Deposition

The films for this work were deposited by coevaporation of BaF_2, Y, and Cu onto a room temperature substrate followed with an ex-situ anneal [5]. The substrate material was $LaAlO_3$ ($\epsilon_r \sim 24$) which was cut to a size of 2 cm × 2 cm × 500 μm. Double-sided deposition was carried out by evaporating on one side of the substrate, breaking vacuum, flipping the substrate, and depositing on the second side. During deposition, the substrate was suspended slightly to prevent contact between the back face and the evaporator stage. After annealing, the resulting films were 3000 A on each side, highly oriented with the c axis normal. X-ray diffraction showed the films to be virtually free of a-axis material, and no basket-weave pattern was visible under microscope. The critical temperature T_c was ~90 K after patterning and the critical current density J_c for similarly deposited films was typically greater than 10^6 A/cm^2 at 77 K. The microstrip circuits were produced by defining the pattern on one side of each film sample with an AZ 1350J photoresist mask and wet-etching with dilute (1%) phosphoric acid. The film on the reverse side was protected from the etchant by a layer of unexposed resist.

III. Resonator Description

Two ring resonator geometries were studied, the two differing in ring diameter. The strip width was the same for both to maintain a fixed line impedance. The mean-ring diameters were 10.5 mm and 5.2 mm giving fundamental resonance frequencies of approximately 2.4 GHz and 4.8 GHz, respectively. The line width was 150 μm to give a characteristic impedance of 50 Ω. The ratios of line width to ring diameter, 0.014 and 0.029, were small enough to ensure that in the frequency range of our measurements (below 23 GHz), only the azimuthal modes (TM_{10}) propagate [6]. The fields on the rings were excited and probed by a pair of diametrically-opposed microstrip lines that were weakly coupled to the resonator by gaps 400 μm and 500 μm wide respectively for the two geometries. The substrates were mounted in a Cu fixture, secured by spring pressure, and In solder connections were made between Ag contact pads that had been deposited on the microstrip ends and the microwave connectors in the housing.

IV. Measurements and Discussion

The packaged resonators were mounted on the stage of a closed-cycle refrigerator and connected to a pair of BeCu 0.034-in. diameter coaxial cables which provided the signal path to the outside. The scattering parameters, S_{21} and S_{11}, were measured up to 23 GHz with an HP 8510B network analyzer in the temperature range 15–90 K. Prior to these measurements, the network analyzer was calibrated at the plane of the device on the cold stage with a set of HP calibration standards and the stage at 295 K. Subsequent measurements were made with the stage cooled to below 80 K to determine the decrease in insertion loss that resulted from cooling the interior cables. With a through connection made on the cold stage, the difference between the room temperature value of $|S_{21}|$ and its low temperature value was <0.2 dB.

The transmission S_{21} for each of the two resonators in the vicinity of the second harmonic at temperatures between 25 and 88 K is shown in Figs. 1(a) and (b). Above T_c, the $Ba_2YCu_3O_7$ behaves as a resistive conductor and a resonance peak is not resolved above the noise. Resonance becomes clearly discernible when the resonator is cooled to just below T_c. By 88 K the losses in the superconductor film decrease below those for gold. As the temperature is reduced further, we observe a rapid

Manuscript received October 8, 1990; revised December 10, 1990.
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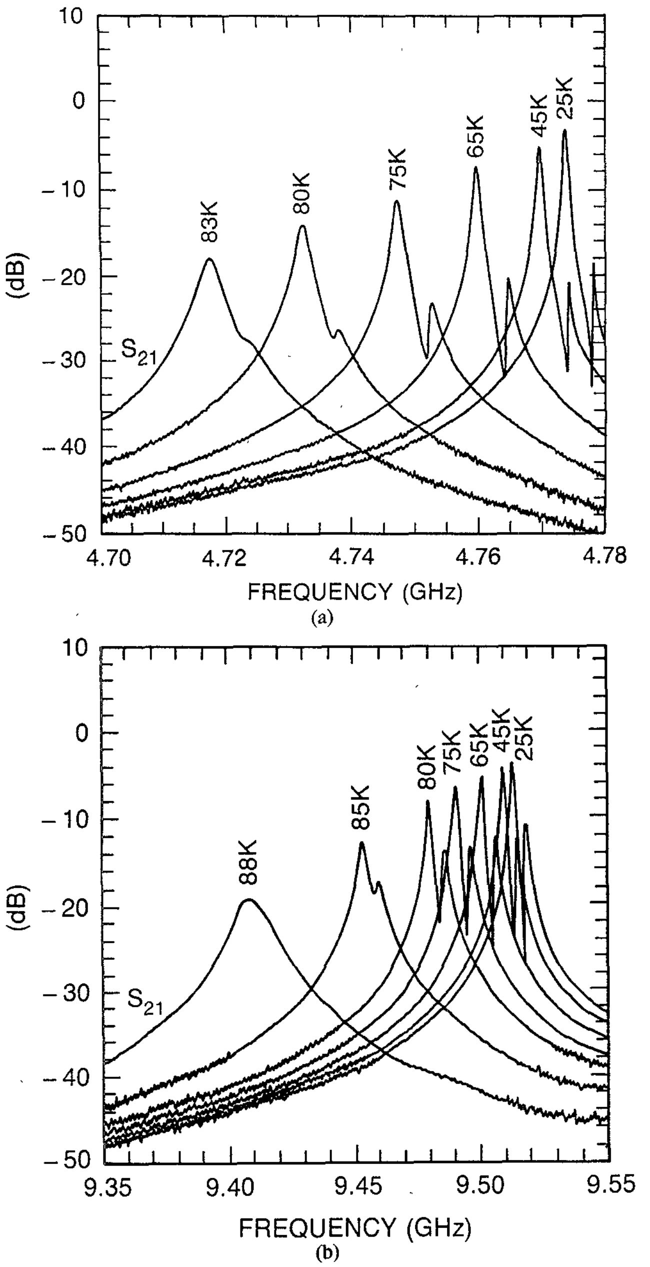

Fig. 1. Magnitude of S_{21} for second harmonic resonances at (a) 4.75 GHz and (b) 9.50 GHz for two resonator geometries described in text measured between 25 K and 90 K.

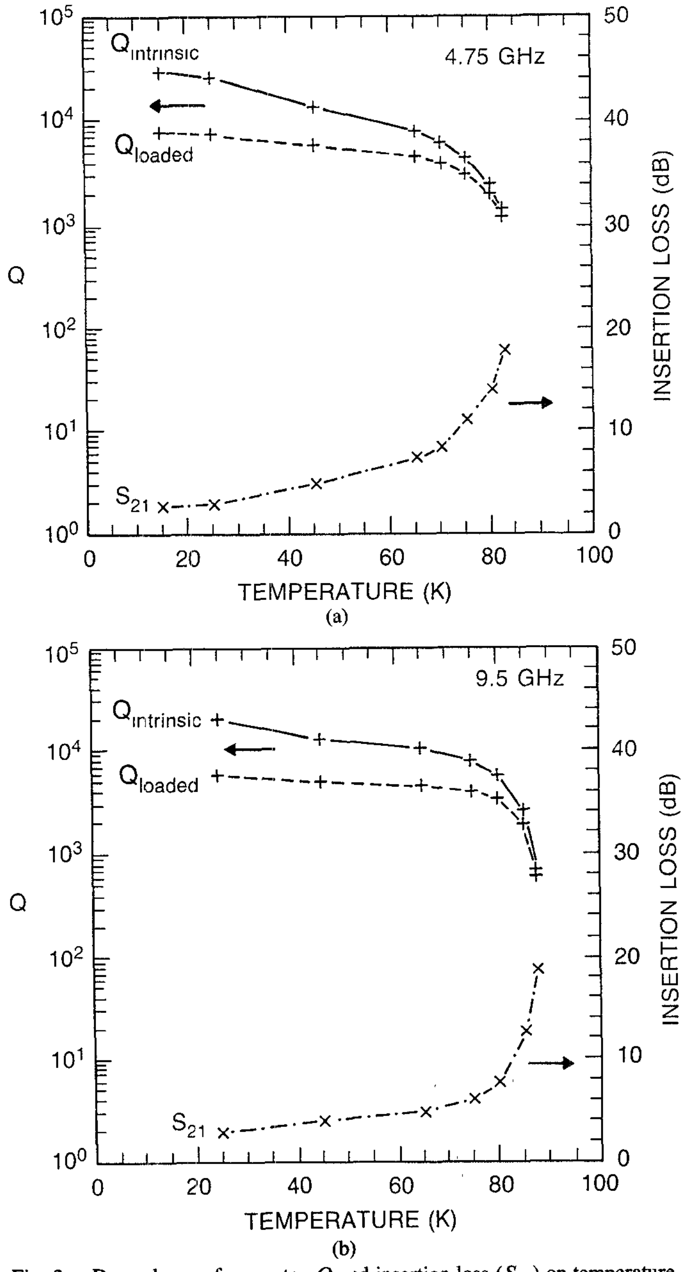

Fig. 2. Dependence of resonator Q and insertion loss (S_{21}) on temperature for (a) 10.5 mm diameter ring at 4.75 GHz and (b) 5.2 mm diameter ring at 9.5 GHz.

decrease in the width of the transmission peak and insertion loss at resonance, and a migration of the resonance peak to higher frequencies. We also observe a second less prominent structure displaced to the high side of the dominant peak by 5–10 MHz.

The temperature dependence of the transmission response is summarized in Figs. 2(a) and (b) where the Q and insertion loss at resonance for various temperatures are plotted. The values for intrinsic Q were calculated from the S parameters at resonance and the width of the transmitted peak at the 3-dB points. The existence of the secondary structure, whose origin is currently under investigation, was of no consequence to this calculation since it is adequately displaced from the primary resonance and its magnitude within the 3-dB bandwidth is negligible. The most rapid changes are observed above 80 K, at which temperature the measured width of the peak is 1.7 times its value at 25 K. For comparison, at 75 K the Q of a similar Au resonator at 10 GHz was a factor 20 lower. For both resonators, the values of intrinsic Q exceed 20 000 at 25 K.

The change in resonant frequency with temperature is shown in Fig. 3 where we plot the fractional shift in frequency normalized to the 25 K value for temperatures between 25–88 K. The data plotted represent the residual frequency shift obtained after accounting for a small contribution due to the substrate temperature dependence. Over this temperature range, we observe a frequency shift of $\sim 1\%$ with the greatest variation occurring above 0.8 T_c. Below 75 K, the change is $\sim 0.1\%$. The same fractional shift was observed for the several harmonics that were measured. We attribute this shift to the change in the inductance per unit length of the line that occurs as a consequence of the decrease in penetration depth, $\lambda(T)$, as the temperature is lowered. The origin of the change in $\lambda(T)$ derives from the increase in the superconducting pair density with decreasing

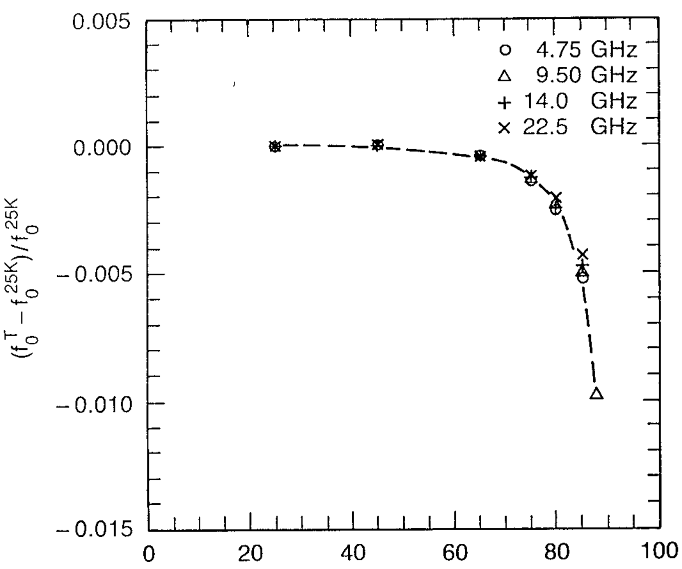

Fig. 3. Fractional change in resonant frequency with temperature at 4.75 GHz (fundamental), 9.5, 14, and 22.5 GHz. Data have been corrected for substrate temperature dependence. Dashed line is two-fluid model fit with $T_c = 89.5$ K and $\lambda(0) = 4500$ A.

temperature. Since the phase velocity varies as the square root of the inductance, we expect the frequencies of resonance to increase with decreasing temperature. For frequencies well below the gap $\lambda(T)$ is not dependent on frequency so the shift should also be frequency independent as is shown by the data.

The correction to account for the change in the substrate with temperature was derived form measurements made over the same temperature range on a gold resonator that had also been deposited on a $LaAlO_3$ substrate. From these measurements, we extracted a constant fractional change due to the substrate of $\sim 2 \times 10^{-5}\ K^{-1}$.

We can express the phase velocity of a microstrip transmission line as in [7]:

$$v_{ph} = \frac{1}{\sqrt{\mu_0 \epsilon_{eff}}} \left[1 + \frac{2\lambda}{d} \coth\left(\frac{b}{\lambda}\right)\right]^{-\frac{1}{2}},$$

where ϵ_{eff} is the effective constant d is the substrate thickness, b is the film thickness, and λ is the penetration depth. Assuming a temperature dependence for λ given by the two-fluid model [8]:

$$\lambda(T) = \lambda(0)\left[1 - \left(\frac{T}{T_c}\right)^4\right]^{-\frac{1}{2}},$$

we can calculate the change in frequency expected with temperature. A fit to the data for the patterned films gives a value for $\lambda(0)$ of 4500 A. The calculated frequency shift is shown by the dashed curve in Fig. 3.

We interpret the value for λ obtained above as an effective penetration depth averaged over the entire film surface including areas where field penetration may be larger than the intrinsic (single crystal) value. This is particularly true along microstrip edges that may have been degraded during patterning and at grain boundary interfaces where flux may penetrate more freely. The effect of degradation due to patterning is of particular concern since it is at the microstrip edges that the current density is the highest. The somewhat higher than intrinsic value for λ obtained here suggests that alternative processing techniques should be investigated.

V. Conclusion

We have demonstrated the feasibility of fabricating high quality microwave circuits from high critical temperature superconductor films that have been deposited on both sides of the same, low-loss substrate by coevaporation. By patterning one side with a narrow ring, we have produced resonators with Q factors at 9.5 GHz in excess of 7500 at 75 K and 20 000 at 25 K. The temperature dependence of the resonant frequency shows the behavior expected for a superconductor with an effective penetration depth of ~ 4500 A. It is important to note that the coevaporation process used to deposit these films can be scaled to large substrate sizes that will be essential for practical microwave applications.

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