Stripline Resonator Measurements of Z_S Versus H_{rf} in $YBa_2Cu_3O_{7-x}$ Thin Films

Daniel E. Oates, *Member, IEEE*, Alfredo C. Anderson, David M. Sheen, and Sami M. Ali, *Senior Member, IEEE*

***Abstract*—We report measurements of the surface impedance, Z_S, of $YBa_2Cu_3O_{7-x}$ thin films using a stripline resonator. The films were deposited on $LaAlO_3$ substrates by off-axis magnetron sputtering. We obtained Z_S as a function of frequency from 1.5 to 20 GHz, as a function of temperature from 4 K to the transition temperature ($\sim$90 K), and as a function of the RF magnetic field from zero to 300 Oe. At low temperatures the surface resistance, R_S, of the films shows a very weak dependence on the magnetic field up to 225 to 250 Oe. At 77 K, R_S is proportional to the square of the field. The penetration depth shows a much weaker dependence on the field than does R_S. At 1.5 GHz the surface resistance of the best films is 2×10^{-6} Ω at 4 K and 8×10^{-6} Ω at 77 K. We also discuss the origins of the magnetic field dependence of Z_S.**

I. Introduction

INTEREST in microwave applications of the high-T_c materials continues to be great because their losses at microwave frequencies and at temperatures as high as 77 K have been shown to be at least an order of magnitude lower than those of copper and because of the expectation, based on theoretical considerations, that their surface resistance, R_S, can be lowered by another factor of 10 to 100 by improvements in material fabrication methods. Many R_S measurements for the high-T_c superconducting materials have been reported in the literature, and films of $YBa_2Cu_3O_{7-x}$ deposited by a variety of methods by numerous laboratories have shown low enough values of R_S to be of practical importance [1]. There have also been numerous reports of practical devices demonstrated with the new materials (see, for example, [2]). Almost all of the reported R_S measurements, however, have been carried out at low power and thus at low values of H_{rf}, the microwave-frequency magnetic field generated by the RF current flowing in the stripline. It has been known for some time that the values of R_S are dependent on the level of microwave power used in the measurement. This has been noted in measurements of Q or R_S in stripline resonators [3] as well as in cavities [4], [5]. Much higher values of H_{rf} can be reached at a given power level in stripline structures than in the usual cavity geometries because the narrow transmission line concentrates the current and leads to higher current density and higher H_{rf}. Until now, however, the measurements of R_S as a function of the input power in stripline structures have not been quantitative because the current distribution in the stripline could not be calculated accurately and hence the exact value of the magnetic field was not known.

Recently completed calculations of current distributions in stripline transmission line structures [6] allow quantitative measurements of R_S versus the peak H_{rf}. Using the results of the calculations and the measured values of Q and the resonant frequency of a stripline resonator, we report here the microwave-frequency surface impedance, Z_S, as a function of frequency from 1.5 to 20 GHz, of temperature from 4 K to the transition temperature ($T_c \approx 90$ K), and of H_{rf} from 0 to 300 Oe. The measurements include determination of R_S as well as λ. Because λ is usually comparable to the thickness, t, of the $YBa_2Cu_3O_{7-x}$ films, the finite value of λ/t must be considered in extracting R_S from the measured resonator Q. In addition, one must know λ to calculate the current distribution in order to obtain the H_{rf}.

The measurements have been carried out on a number of $YBa_2Cu_3O_{7-x}$ films deposited *in situ* by single-target off-axis magnetron sputtering. The measurements of $R_S(H_{\mathrm{rf}})$ have shown that the best epitaxial films exhibit a weak dependence of R_S on H_{rf} while films of lower quality, believed to be composed of grains connected by weak links, show an R_S that increases in linear proportion to H_{rf}. The films exhibit a critical field, beyond which the surface resistance increases sharply, indicating that a substantial fraction of the line has become normal. In the best films the field at which this happens is approximately 250 Oe, which is higher than any previously reported value.

The magnetic field dependence of R_S below the critical field leads to the generation of nonlinear effects at power levels well below those that approach the critical field. We report here measurements of the intermodulation products in the resonators and show that the films with a lower dependence of R_S on H_{rf} show lower generation of

Manuscript received March 12, 1991. This work was supported by the Defense Advanced Research Projects Agency (Contract MDA972-90-c-0021) under the auspices of the Consortium for Superconducting Electronics.
D. E. Oates and A. C. Anderson are with Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.
D. M. Sheen and S. M. Ali are with the Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139.
IEEE Log Number 9101200.

0018-9480/91/0900-1522$01.00 ©1991 IEEE

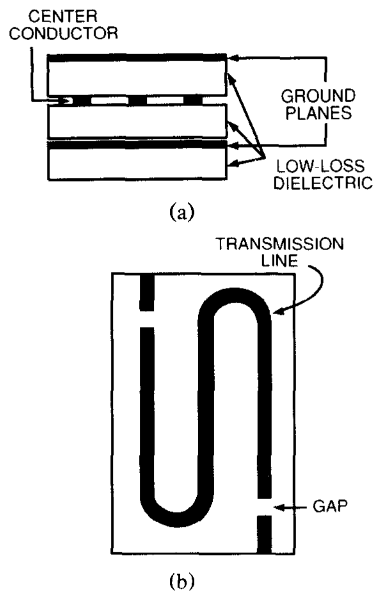


Fig. 1. Schematic (a) cross-sectional and (b) top views of the stripline resonator used in the measurements.

intermodulation products and thus higher values of the third-order intercepts.

II. Stripline Resonators

Our measurements of Z_S were made using the stripline resonator structure shown in Fig. 1. Stripline is defined as having a center conductor, an upper and lower ground plane, and a symmetric dielectric. The resonator consists of a length of transmission line, patterned by photolithography, one half wavelength long at the fundamental frequency; overtone resonances occur at all multiples of the fundamental frequency. The Q and the resonance frequency of all the overtone modes of the resonator were measured using transmitted power. The resonator is capacitively coupled to the external circuit by gaps at the two ends of the stripline. The gaps are adjusted so that the resonator is weakly coupled and only small corrections have to be made to Q_L, the loaded Q, to obtain Q_U, the unloaded Q. The length of line was chosen to yield a fundamental frequency, f_0, of 1.5 GHz. The line width is 150 μm. This gives a 34 Ω transmission-line impedance with 0.5-mm-thick $LaAlO_3$ as the dielectric ($\epsilon = 25$). The dimensions of the substrates are 1×1 cm^2. Because of the presence of upper and lower ground planes, the radiation losses are lower in stripline than in any other transmission line geometry, and the ground planes confine the field almost completely so that stray coupling to other conductors and consequent additional loss are virtually eliminated.

The resonator is fabricated from three separate films on three substrates clamped together in a copper package with RF connectors on it. The measured Z_S contains contributions from all three films used so that Z_S is a weighted average, with the center conductor contributing about 80%.

In cavity resonators and certain types of parallel-plate resonators, substrate losses are usually unimportant because the fields do not penetrate them. In stripline resonators, however, because the RF fields penetrate the substrates they must have low dielectric losses [3]. In order for the substrate losses to be negligible, $\tan\delta$ must be less than $1/Q$ of the resonator. The unloaded Q is given by $1/Q_U = 1/Q_C + \tan\delta$, where Q_C is the conductor Q. Since $\tan\delta$ is relatively independent of frequency and Q_C for superconducting films is proportional to $1/f$, we can verify at any particular temperature that the substrate losses are not limiting the measured Q by measuring the Q versus f and observing the appropriate frequency dependence. As discussed below, we expect that $R_S \propto f^2$ and hence $Q \propto 1/f$ for losses that are dominated by the superconductor. A Q independent of frequency indicates that the substrate losses are dominant. In all of our measurements the Q appears to be determined by the conductor losses and not the substrate losses.

III. $YBa_2Cu_3O_{7-x}$ Films

The films used to make the resonators reported here have been fabricated by an off-axis magnetron sputtering process that has been reported previously [7]. We concentrate here on results from two sets of films deposited at 760° C but with different sputtering targets. These have the best microwave properties among our films. Other films have been reported previously [3], [8]. The substrate is $LaAlO_3$.

IV. Current Distribution

The method of calculating the current distribution, described in detail in [6], is based on a modification of the Weeks [9] method and incorporates a complex conductivity to describe the superconductor and ensure that the London equations as well as Maxwell's equations are satisfied. The calculations can be applied to any number of coupled superconductors in a quasi-TEM system. The calculations are also valid for both high- and low-T_c materials. From the current distribution, the inductance per unit length, L, and resistance per unit length, R, of the conductors can be calculated for a particular geometry and as a function of penetration depth, λ. For small λ, the inductance and the relation between Q and R_S are nearly independent of λ. Fig. 2 shows the results of the calculations of the current distribution for the geometry of the stripline used in these experiments, described in Section II. These calculations are for $\lambda = 0.16$ μm and for a film thickness $t = 0.3$ μm. As seen, the currents are highly nonuniform, especially in the center conductor where the currents are crowded to the edges with the scale of the penetration from the edge determined by λ. For smaller λ, the currents are more strongly peaked at the edges, and for larger λ the current distribution becomes more uniform. In the ground planes the current is spread out and about ten times wider than in the center

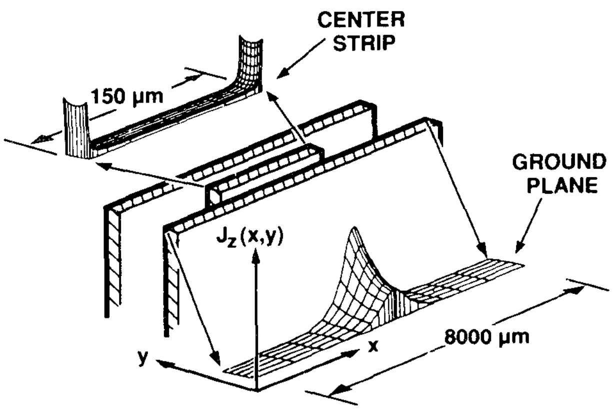


Fig. 2. Calculated current distributions for center conductor and ground plane of the resonator used in these experiments. Note the different scales for the center strip and the ground plane. The calculations are for $\lambda = 0.16$ μm and film thickness $t = 0.30$ μm.

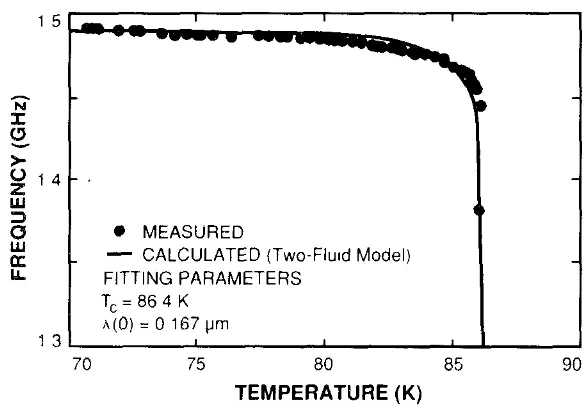


Fig. 3. Measured and calculated values of resonant frequency of the fundamental mode of the resonator versus temperature for $YBa_2Cu_3O_{7-x}$ film (sample 1 in Table I). The calculated values use the two-fluid model. The best fit is obtained with $\lambda(0) = 0.167$ μm and $T_c = 86.4$ K.

conductor. Since losses are proportional to the square of the current density, it is obvious that the largest contribution to the losses is the center conductor.

The calculated resistance and inductance values may be used to extract both λ and the intrinsic surface resistance, R_S, of the superconductors from the measured Q of the stripline resonator. From the current distribution we can also calculate H_{rf}, the RF magnetic field throughout the resonator. This is the self-field resulting from the RF current flowing, as discussed below.

V. Measurements of Z_S

A. Penetration Depth

We determined λ by measuring the temperature dependence of the fundamental resonant frequency of the resonator and then fitting a model of the temperature dependence of λ to the measured data. The resonant frequency is proportional to $1/L^{0.5}$, where L is the inductance per unit length calculated from the current distribution. Fig. 3 shows the measured resonant frequency versus temperature for one of the films (sample 2 in Table I).

TABLE I
Parameters of Films

Film	Sample	$\lambda(0)$ (μm)	T_c (K)
$YBa_2Cu_3O_{7-x}$	#1	0.22	90
$YBa_2Cu_3O_{7-x}$	#2	0.167	86.4
Sputtered Nb	—	0.070	9.2

The solid line is a least-squares fit to the data using the temperature dependence calculated from the two-fluid model and using $\lambda(T=0) \equiv \lambda_0$ as a free parameter. In the two-fluid model,

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}$$

where T_c is the transition temperature. T_c was taken to be 86.4 K, which gives the best fit and is consistent with the measured resistive transition. The resonant frequency, f, is given by

$$f(T) = f(T_0)\sqrt{\frac{L(\lambda(T_0))}{L(\lambda(T))}} \tag{1}$$

where $L(\lambda)$ was obtained from the calculated values. The best fit is obtained with $\lambda_0 = 0.167$ μm. The fit shows some deviation from the two-fluid model, as others have observed [10]. Determination of λ in this manner has an approximate accuracy of 20% and is model dependent. The inferred value of λ is also highly sensitive to the value of T_c chosen. For instance, a shift of 0.1 K in T_c can change λ_0 by 10%.

Table I shows the measured values of λ for a sputtered niobium film, which was used as a check of the method, as well as the values for the two sputtered $YBa_2Cu_3O_{7-x}$ films. The value of λ obtained for sputtered niobium agrees with previously reported values.

B. Surface Resistance at Low RF Fields

To obtain the surface resistance of the films, we use λ, determined as described in subsection V-A, to calculate L, the inductance per unit length of the stripline, and σ_2, the imaginary part of the complex conductivity. Then, the measured Q and L are used to obtain R, the resistance per unit length, from the expression $Q = \omega L/R$. R and λ are used to find σ_1, the real part of the complex conductivity, and R_S is obtained from $R_S = \omega^2\mu^2\sigma_1\lambda^3/2$, where μ is the permeability. For small λ/t the relationship between Q and R_S is independent of λ, and R_S is given by

$$R_S = \frac{\Gamma f}{Q} \tag{2}$$

where Γ is a geometrical factor, which in the stripline used here is equal to 0.41 Ω/GHz. When λ/t becomes

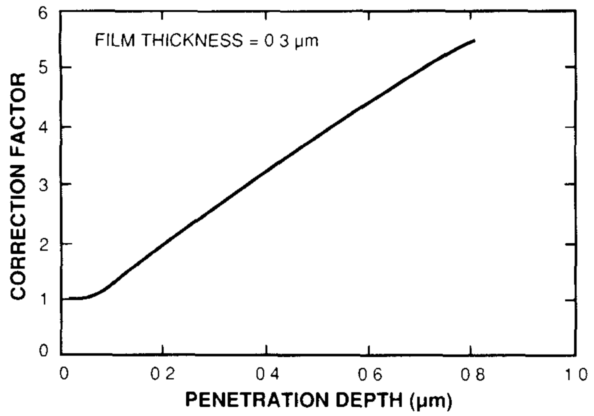


Fig. 4. $\Delta(\lambda/t)$ versus penetration depth for $t = 0.30$ μm. $\Delta(\lambda/t)$ is the correction factor to R_S defined in (3).

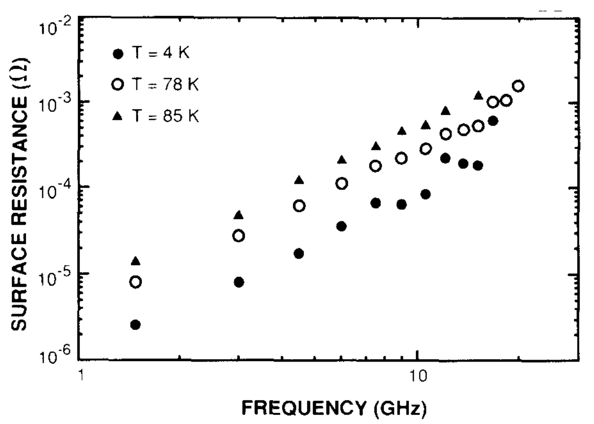


Fig. 5. Surface resistance versus frequency for three different temperatures, as indicated. These results are for the best sputtered film (sample 1 in Table I).

comparable to unity, (2) must be modified to

$$R_S = \frac{\Gamma f}{\Delta\left(\frac{\lambda}{t}\right) Q} \tag{3}$$

where $\Delta(\lambda/t)$ is a correction factor to take into account the dependence of R and L on λ. This correction factor is shown in Fig. 4 for a film of thickness 0.3 μm.

1) Frequency Dependence: Fig. 5 shows for the best of the sputtered films (sample 1 in Table I) the frequency dependence of the surface resistance at low RF fields, with temperature as a parameter. Each point in the plot corresponds to one of the modes of the resonator. The R_S increases very nearly as the square of the frequency. Many models of losses in superconductors, including the two-fluid model [11] and others based on losses in intergrain weak links [12], predict an f^2 dependence of R_S, so this result is expected and does not differentiate between the various proposed models of RF losses. The R_S in Fig. 5 was determined as described in the previous paragraph and all substrate losses were ignored. Since for all temperatures the R_S shows a quadratic increase with frequency, the assumption of negligible substrate losses is

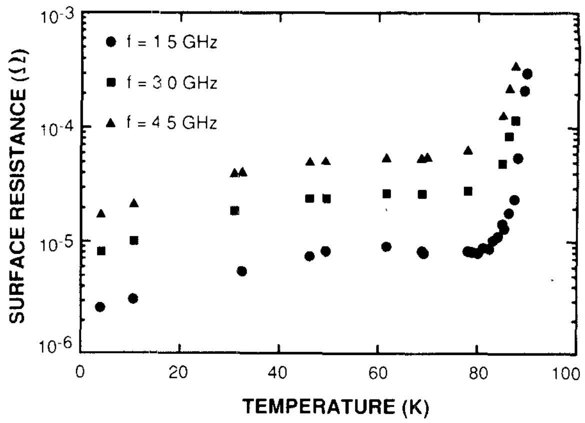


Fig. 6. Surface resistance versus temperature for the first three modes of the best sputtered film (sample 1 in Table I). The frequency of each mode is given.

justified. If the substrate losses were appreciable, R_S calculated in this manner would show a linear increase with frequency since the $\tan\delta$ for most dielectrics is nearly independent of frequency. A Q that is independent of frequency yields, from (1), a R_S that is linearly proportional to the frequency. From the conclusion that $\tan\delta \ll Q_C^{-1}$ and from the measured Q's of 100000 at 4 K and 25000 at 77 K, we can set upper limits to $\tan\delta$ for $LaAlO_3$ of approximately 5×10^{-6} at 4 K and 10^{-5} at 77 K.

2) Temperature Dependence: Fig. 6 shows the temperature dependence of the low-field surface resistance for the first three modes of the best film. The results show the usual sharp decrease in R_S just below T_c, followed by a region with R_S relatively independent of temperature. Interestingly, however, the curve exhibits a plateau, after which, at low temperatures, R_S again falls slightly. Similar behavior has recently been reported in other films [13]. This behavior at low temperatures is not understood because the usual explanation of the flat R_S versus T curve for temperatures below about 77 K is that the values are dominated by a residual resistance which is independent of temperature. We believe that the shape is not an artifact of the measurements or substrate losses because the three frequencies have identical shapes. Also, the three curves are separated very nearly by the ratios 1:4:9, indicating that the measurements are the result of the losses in the superconductor following an f^2 behavior.

It should be pointed out that the values of surface resistances shown in Figs. 5 and 6 are among the best reported values [14], [15]. We also believe that these are the lowest reported values for a patterned film.

C. Z_S at High RF Fields: $R_S(H_{rf})$ and $\lambda(H_{rf})$

1) Measurements of $R_S(H_{rf})$: To obtain $R_S(H_{rf})$, we measure the Q of the resonator as a function of the incident RF power. Knowing the Q, the insertion loss of the resonator, and the incident power, we can then calculate the total RF current in the stripline at the peaks of

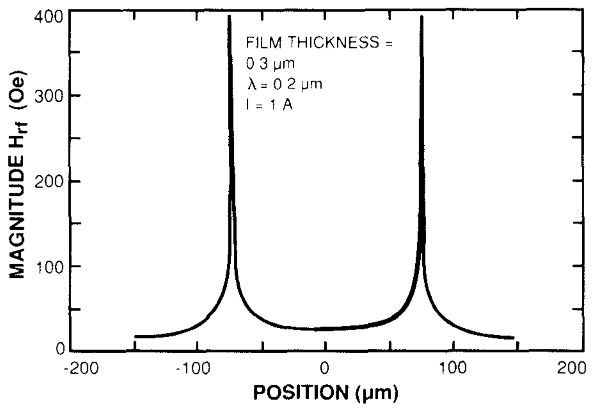


Fig. 7. Magnetic field at the surface of the center strip in the stripline resonator. Calculations are for $\lambda = 0.2$ μm and film thickness $t = 0.3$ μm with a total current of 1 A.

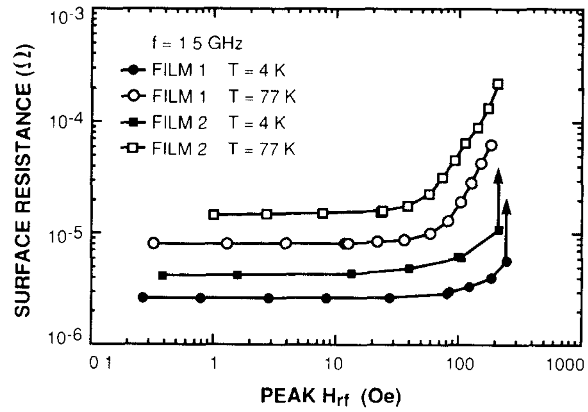


Fig. 8. R_S versus peak H_{rf}, the peak field at the edges of the center strip, for the two $YBa_2Cu_3O_{7-x}$ films (samples 1 and 2 in Table I) at 4 and 77 K. The frequency in all cases is 1.5 GHz.

the standing wave maxima at resonance by [3]

$$|I| = \sqrt{\frac{r_v(1-r_v)4Q_C P}{n\pi Z_0}}$$

where r_v is the voltage insertion ratio, related to the insertion loss, IL, by $IL = -20\log r_v$, Q_C is the conductor Q, P is the incident power, n is the resonant mode number, and Z_0 is the characteristic impedance of the line. From the total current and the calculated current distribution, the RF magnetic field at the surface of the conductors can easily be calculated. Fig. 7 shows the magnetic field distribution at the surface of the center conductor for our geometry for a current of 1 A. As can be seen, the field distribution is peaked near the edges like the current density.

Fig. 8 shows the dependence of R_S on H_{rf} for the two $YBa_2Cu_3O_{7-x}$ sputtered films. In each case the H_{rf} given is the maximum field found near the edges of the center strip. We show data for $f = 1.5$ GHz at 4 and 77 K for both films. At 4 K for both films the input power was increased until a sharp increase in R_S was measured. Beyond this point it is meaningless to report values of R_S because the resonance curve is severely distorted and Q is ill defined. At 77 K no sharp increase in R_S was noted up to the maximum available input power of 1 W. At 4 K below the apparent critical field, and at 77 K over the entire range, the R_S is well approximated by a quadratic dependence on H_{rf},

$$R_S = R_{S0} + \alpha H_{rf}^2$$

where R_{S0} is the surface resistance at very low fields. In postannealed films and in films sputtered at lower sample temperatures, which we have previously reported [3], we have observed a linear dependence of R_S on H_{rf}:

$$R_S = R_{S0} + \beta H_{rf}.$$

A linear dependence of R_S on H_{rf} has been associated with magnetic flux penetration in Josephson-junction-type weak links between grain boundaries [16]. Such dependence is a signature of a film that is not single crystal in nature but is composed of a collection of weakly connected grains. A quadratic dependence of R_S on H_{rf}, on the other hand, is consistent with Ginsburg–Landau theory [11], in which the magnetic field breaks superconducting pairs, increases the proportion of normal electrons, and thus increases the surface resistance. The weak quadratic field dependence at low temperature indicates that these newer films sputtered at higher substrate temperatures are relatively free of weak links and more nearly single crystal than the earlier examples.

A temperature rise in the film would also cause an increase in the R_S when the power input to the resonator is increased. To minimize heating effects, the measurements were performed only with the resonator completely immersed in liquid helium for 4.2 K and in liquid nitrogen for 77 K. At each power level the sweep time of the network analyzer was decreased to see if the resonance curve or Q changed in any way. For all of the reported data the Q was independent of sweep time, even at the longest time of 50 s/sweep. The severely distorted resonance curves at 4 K beyond the point identified with the critical current are also independent of sweep rate. We have, however, observed heating effects at the very highest power levels beyond the critical current when energy dissipation in the films has increased markedly. Because there is a minimum sweep time (~ 5 s/sweep) established by the internal circuitry of the network analyzer, we have not ruled out the possibility of heating effects that reach equilibrium in times shorter than the time constants of the network analyzer. Such effects are very difficult to measure using frequency-domain techniques. In addition, because the time constant for buildup of the current in the resonator is $Q/\pi f$, heating effects on time scales shorter than this can only be observed by measuring departures from a pure exponential rise in current in the time domain. We are currently pursuing time-domain measurements in order to rule out heating effects completely.

2) Measurements of $\lambda(H_{rf})$: By measuring the change in the center frequency as a function of the RF power and using the calculations of the stripline inductance $L(\lambda)$, we

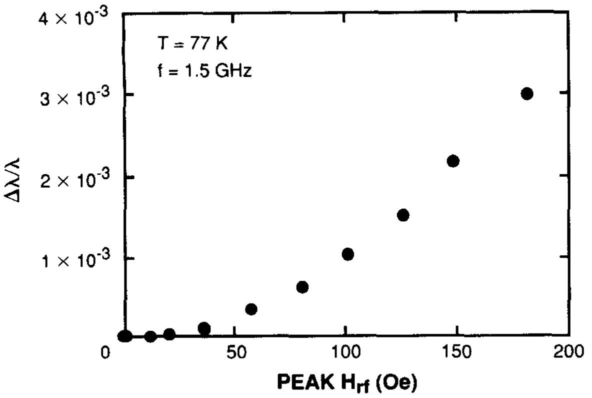


Fig. 9. λ versus peak H_{rf} at 77 K for the best film (film 1 in Fig. 8).

can calculate the change in penetration depth as a function of the RF magnetic field. From the dependence of resonant frequency on inductance we obtain the fractional change in frequency, given by

$$\frac{\Delta f}{f} = \sqrt{L(\lambda)}\,\frac{d}{d\lambda}\left(\frac{1}{\sqrt{L(\lambda)}}\right)\Delta\lambda.$$

Then the fractional change in λ can be related to the measured $\Delta f/f$ by

$$\frac{\Delta\lambda}{\lambda} = -\frac{2L}{\lambda\left(\dfrac{dL}{d\lambda}\right)}\frac{\Delta f}{f}.$$

Fig. 9 shows the results of the fractional change in λ versus H_{rf} at 77 K for the film labeled 1 in Fig. 8. At 4 K, $\Delta\lambda/\lambda$ is even smaller. The fractional change in λ is smaller than the change in R_S, and the change in λ is not nearly large enough to explain the change in R_S. As in the case of R_S, λ is approximately proportional to the square of H_{rf}.

VI. Intermodulation Products

When R_S depends upon the magnetic field and thus the power carried by the material, nonlinear effects can be observed even at the relatively low power levels typically found in band-pass filters, because the dependence of R_S on H_{rf} extends down to very low values of field as seen in Fig. 8. Harmonic and intermodulation product generation result. Fig. 10 shows measurements of the intermodulation products in resonators made from two sputtered film sets (film 3 and film 2). Film 3, reported earlier [3], shows a linear dependence of R_S on H_{rf}, and film 2 (same as film 2 in Fig. 8) shows a very weak dependence on H_{rf}. This was a standard two-tone intermodulation test where two tones of equal power, one at f_1 and the other at f_2, are the input. A frequency of $2f_1 - f_2$ is observed, where f_1, f_2, and $2f_1 - f_2$ are all within the passband of the resonator. For these measurements, $f_1 - f_2 = 1$ kHz and the fundamental mode $f = 1.5$ GHz were used. The third-order intercept, which is the intersection of the extrapolation of slope = 1 connecting the measured outputs at f_1 and slope = 3 connecting the points measured at $2f_1 - f_2$, is the usual measure of the nonlinearities of a particular device. One sees that the third-order intercept in the $YBa_2Cu_3O_{7-x}$ resonator made with the films of low H_{rf} dependence is approximately 15 dB higher than that of the film having a large H_{rf} dependence. This is a demonstration that lower H_{rf} dependence leads to improved practical performance. Although not shown in Fig. 10, a niobium resonator demonstrates better performance than the best $YBa_2Cu_3O_{7-x}$ resonator, probably because the critical field is higher.

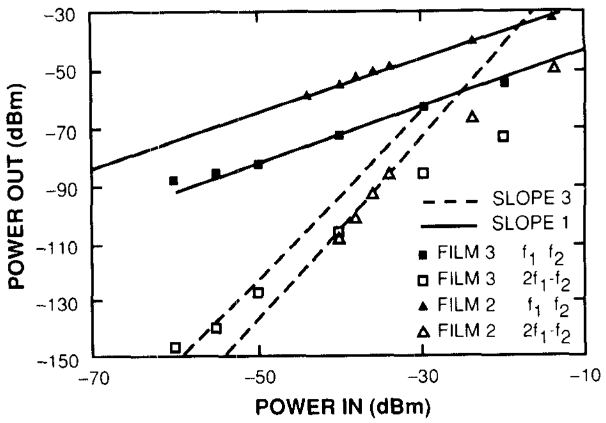


Fig. 10. Intermodulation measurements for two $YBa_2Cu_3O_{7-x}$ films. Film 3 shows a linear dependence of R_S on H_{rf} while film 2 (film 2 in Fig. 8) shows a very weak quadratic dependence of R_S on H_{rf}. The frequency is 1.5 GHz.

VII. Discussion

The quadratic field dependence of the surface resistance is that predicted by the Ginsburg–Landau (GL) theory. But it is difficult to explain our results using this theory, since at low temperature the surface resistance is dominated by the residual resistance that results from extrinsic effects. We expect therefore that any pair-breaking effects described by GL theory will be masked entirely by the residual resistance [16]. In addition, the GL theory leads to a larger fractional change in R_S at low temperatures, where most electrons are already paired, and any breaking of pairs will have a proportionally larger effect than at 77 K, where there are already many unpaired electrons. Thus, it is difficult to explain qualitatively the temperature dependence of the $R_S(H_{rf})$ from the GL theory.

The physical mechanism for the H_{rf}^2 dependence is not known. It may be that different mechanisms govern the behavior at low and high temperatures. For example, if the sudden increase in R_S observed at high fields at low temperature were due to flux becoming unpinned at the edges of the stripline, then at higher temperatures, one would expect a more gradual effect (as we have observed) because the flux is not as strongly pinned and thermal activation is sufficient to de-pin the flux at more moderate values of the fields [17]. Other experimenters [4], [5], [16] have observed a quadratic dependence at low fields

TABLE II
BEST VALUES OF R_S*

Frequency (GHz)	Temperature (K)	R_S (Ω)
1.5	4	2.6×10^{-6}
1.5	77	8.3×10^{-6}
10	4	8.5×10^{-5}
10	77	2.0×10^{-4}

*For sample 1 in Table I.

but in all cases known to us the quadratic dependence changes to a linear dependence at very low fields.

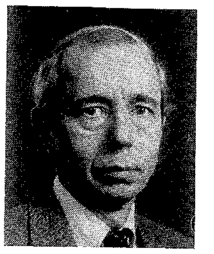
We have presented earlier [3] the results for $R_S(H_{rf})$ in postannealed films and sputtered films deposited at lower temperatures. In both cases R_S was shown to be linearly dependent on H_{rf}, and we proposed that this is due to the penetration of flux at the grain boundaries. In the newer films deposited at higher temperatures there is a very much lower dependence of R_S on H_{rf}, which we explain by lowered contributions from the grain boundaries since higher temperatures lead to better growth conditions of the films.

VIII. SUMMARY

We have deposited films of $YBa_2Cu_3O_{7-x}$ and characterized the microwave properties in a stripline resonator. The values of surface resistance at low RF magnetic field are comparable to the best reported values in the literature. Table II summarizes the results at 1.5 and 10 GHz at 4 and 77 K for the best film (sample 1 in Table I). These results are as low as any values previously reported for a patterned film. Our experimental observations of $Z_S(H_{rf})$ in $YBa_2Cu_3O_{7-x}$ epitaxial thin films are that at 4 K, R_S and λ are very weakly dependent on the RF magnetic field, H_{rf}, up to a critical field value beyond which R_S increases very rapidly; at 77 K, there is a larger quadratic increase of R_S and λ with H_{rf}, and the fractional change in R_S is much larger than that in λ. We did not see the saturation of the R_S versus H_{rf} (R_S becomes independent of field) that others have observed [4], [5], even though our measurements were at higher RF magnetic fields. The physical mechanisms of the critical field effect and the quadratic field dependence have not yet been adequately explained.

REFERENCES

[1] H. Piel, "Microwave surface impedance," *IEEE Trans. Magn.*, vol. 27, pp. 854–862, 1991.
[2] W. G. Lyons *et al.*, "High-T_c superconducting microwave filters," *IEEE Trans. Magn.*, vol. 27, pp. 2537–2539, 1991.
[3] D. E. Oates, A. C. Anderson, and P. M. Mankiewich, "Measurement of the surface resistance of $YBa_2Cu_3O_{7-x}$ thin films using stripline resonators," *J. Superconduct.*, vol. 3, pp. 251–259, 1990.
[4] A. M. Portis *et al.*, "Power- and magnetic field-induced microwave absorption in Tl-based high-T_c superconducting films," *Appl. Phys. Lett.*, vol. 58, pp. 307–309, 1991.
[5] D. W. Cooke, P. N. Arendt, E. R. Gray, and A. M. Portis, "Absorption at high microwave power by large area Tl-based superconducting films on metallic substrates," to be published.
[6] D. M. Sheen, S. M. Ali, D. E. Oates, R. S. Withers, and J. A. Kong, "Current distribution for superconducting strip transmission lines," *IEEE Trans. Appl. Superconduct.*, vol. 1, pp. 108–115, 1991.
[7] A. C. Westerheim, L. S. Yu-Jahnes, and A. C. Anderson, "Off axis magnetron sputtering of YBCO films: The influence of atomic oxygen," *IEEE Trans. Magn.*, vol. 27, pp. 1001–1005, 1991.
[8] D. E. Oates and A. C. Anderson, "Surface impedance measurements of $YBa_2Cu_3O_{7-x}$ thin films in stripline resonators," *IEEE Trans. Magn.*, vol. 27, pp. 867–871, 1991.
[9] W. T. Weeks, L. L. Wu, M. F. McAllister, and A. Singh, "Resistive and inductive skin effect in rectangular conductors," *IBM J. Res. Develop.*, vol. 23, pp. 652–660, 1979.
[10] S. M. Anlage *et al.*, "Magnetic penetration depth measurements with the microstrip resonator technique," *J. Superconduct.*, vol. 3, pp. 251–259, 1990.
[11] T. Van Duzer and C. W. Turner, *Principles of Superconductive Devices and Circuits*. New York: Elsevier North Holland, 1981.
[12] T. L. Hylton and M. R. Beasley, "Effect of grain boundaries on magnetic field penetration in polycrystaline superconductors," *Phys. Rev. B*, vol. 13, pp. 9042–9048, 1989.
[13] G. Müller, private communication.
[14] N. Newman *et al.*, "$YBa_2Cu_3O_{7-x}$ superconducting films with low microwave surface resistance over large areas," *Appl. Phys. Lett.*, vol. 57, pp. 520–522, 1990.
[15] N. Klein *et al.*, "Millimeter wave surface resistance of epitaxially grown $YBa_2Cu_3O_{7-x}$ thin films," *Appl. Phys. Lett.*, vol. 54, 757, 1989.
[16] J. Halbritter, "RF residual losses, surface impedance, and granularity in superconducting cuprates," *J. Appl. Phys.*, vol. 68, pp. 6315–6326, 1990.
[17] T. Orlando, private communication.



Daniel E. Oates (M'87) received the B.A. degree in physics from Yale University in 1965 and the Ph.D. degree in physics from the Massachusetts Institute of Technology in 1971. He held an Alexander von Humboldt fellowship at the University of Bonn, Federal Republic of Germany, in 1971 and 1972.

From 1973 to 1978 he was with Bell Laboratories in Holmdel, NJ. Since 1978 he has been at Lincoln Laboratory. His research interests include the fundamental properties of superconductors at microwave frequencies and the application of superconducting electronics to frequency control and analog signal processing.

Alfredo C. Anderson, photograph and biography not available at the time of publication.

David M. Sheen was born in Richland, WA, on March 6, 1964. He received the B.S. degree in electrical engineering from Washington State University in December 1985 and the M.S. degree in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in September 1988. He is currently studying for the Ph.D. degree in the Department of Electrical Engineering and Computer Science at MIT. His research interests are in the areas of microwave engineering and numerical solution of electromagnetic wave propagation problems.

Sami M. Ali (M'79–SM'86) received the Ph.D. degree in electrical engineering from the Technical University of Prague, Prague, Czechoslovakia, in 1975.

From 1965 to 1985, he was with the Electrical Engineering Department, Military Technical College, Cairo, Egypt. From 1981 to 1982, he spent a sabbatical leave as a visiting scientist at the Massachusetts Institute of Technology, Cambridge. In 1985, he became a Professor and head of the Basic Electrical Engineering Department at the Military Technical College, Cairo. From 1987 to 1989, he was a visiting scientist at MIT and joined the research staff there in 1989. His current research interests deal with microwave integrated circuits and microstrip antennas.

Dr. Ali is currently serving as a member of the International Advisory Board of the Elsevier book series on Progress In Electromagnetics Research (PIER).