

Comparison of Power Dependence of Microwave Surface Resistance of Unpatterned and Patterned YBCO Thin Film

Hao Xin, Daniel E. Oates, *Member, IEEE*, A. C. Anderson, R. L. Slattery, G. Dresselhaus, and M. S. Dresselhaus

Abstract—The effect of the patterning process on the nonlinearity of the microwave surface resistance R_S of YBCO thin films is investigated in this paper. With the use of a sapphire dielectric resonator and a stripline resonator, the microwave R_S of YBCO thin films was measured before and after the patterning process, as a function of temperature and the RF peak magnetic field in the film. The microwave loss was also modeled, assuming a J_{rf}^2 dependence of $Z_S(J_{rf})$ on current density J_{rf} . Experimental and modeled results show that the patterning has no observable effect on the microwave residual R_S or on the power dependence of R_S .

Index Terms—High-temperature superconductors, superconducting films, superconducting materials measurements, superconducting microwave devices, superconducting resonators.

I. INTRODUCTION

THE nonlinearity (power dependence) of the microwave (RF) surface impedance Z_S of the high- T_c superconductors is important for both practical applications and fundamental materials understanding. Nonlinearity in the surface impedance not only degrades the power-handling ability of devices, but also causes intermodulation and harmonic generation problems at moderate power levels. There has been a large amount of effort to investigate the nonlinear Z_S , but the origins of these phenomena are still not understood. Since most of the measurements have been performed on photolithographically patterned stripline or coplanar-waveguide devices, one of the suggested explanations for the nonlinearity is defects and damage caused by patterning. All patterned devices have some current crowding near their edges. For example, stripline and microstrip devices have current distributions that peak sharply near their edges, where the patterning processes have a relatively large influence.

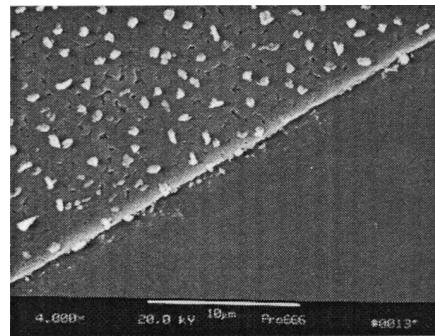


Fig. 1. SEM photograph of the edge of a patterned YBCO stripline.

An SEM picture focusing on the edge of a patterned YBCO thin film is shown in Fig. 1. The edge is not straight, as can be seen in this figure, and the roughness of the edge is of the order of a superconducting penetration depth. This edge roughness results from the initial imperfections of the photoresist pattern and from nonuniformities of the etching process. The edge roughness led to the speculation that the condition of the YBCO line edge was influencing the power dependence, and this was the initial motivation for this paper. The bright particles on the surface of the YBCO film are the well-known copper–oxide outgrowths that are present in all films whose stoichiometry is not exact [1]. We have found that outgrowths do not adversely affect the microwave properties and, therefore, it is unnecessary to make efforts to deposit films with the correct stoichiometry. We have also observed that improvement of the surface morphology to make smoother films than that shown in Fig. 1 does not improve their microwave properties, either with regard to their residual R_S or their power dependence.

In this paper, we used both a sapphire dielectric resonator and a stripline resonator to directly compare the power dependence of the microwave surface resistance R_S of the *same* YBCO thin films, first unpatterned in a dielectric resonator and then patterned in a stripline resonator. Experimental procedures and results are presented in the following sections. To help understand our experimental results better, we have also modeled the R_S , as measured in the dielectric resonator and in the stripline resonator using the following simple phenomenological assumption:

$$\rho(\vec{r}) = \rho_0 + \rho_2 J_{rf}(\vec{r})^2 \quad (1)$$

$$\lambda(\vec{r}) = \lambda_0 + \lambda_2 J_{rf}(\vec{r})^2 \quad (2)$$

Manuscript received January 30, 2000. This work was supported by the Air Force Office of Scientific Research.

H. Xin is with the Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA., and is also with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420 USA, and the Air Force Research Laboratory, Hanscom AFB, Bedford, MA 01731 USA.

D. E. Oates is with the Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA., and also with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420 USA.

A. C. Anderson and R. L. Slattery are with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420 USA.

G. Dresselhaus is with the Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA., and is also with the Air Force Research Laboratory, Hanscom AFB, Bedford, MA 01731 USA.

M. S. Dresselhaus is with the Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

Publisher Item Identifier S 0018-9480(00)05545-9.

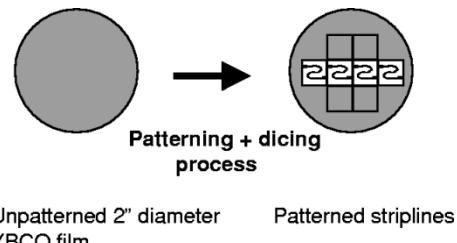


Fig. 2. YBCO film before (left-hand side) and after (right-hand side) the patterning and dicing processes.

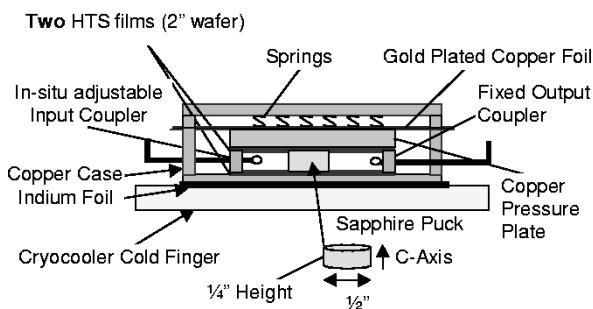


Fig. 3. Structure of the dielectric resonator.

where $\rho(\vec{r})$ and $\lambda(\vec{r})$ are, respectively, the real part of the complex local resistivity and the penetration depth, $J_{rf}(\vec{r})$ is the local current density in the film, and ρ_2 and λ_2 are the corresponding nonlinear coefficients obtained by fitting the data.

II. EXPERIMENTAL METHOD

In order to study the effects of defects and damage introduced in the patterning process on the power dependence of the microwave surface resistance of YBCO thin films, we measured the nonlinear microwave-frequency surface resistance at 10.7 GHz of unpatterned 2-in-diameter 400-nm-thickness YBCO films using a specially designed sapphire dielectric resonator. The YBCO films were deposited by a dc magnetron sputtering method [2] on an LaAlO_3 substrate with a thickness of 0.5 mm. The unpatterned films were then patterned using standard photolithography and wet chemical etching with 0.1% phosphoric acid to make stripline resonators with resonant frequencies $f_0 = nf_1$, where $n = 1, 2, \dots$, and $f_1 = 1.5$ GHz. The patterning and dicing procedures are described in Fig. 2. The microwave surface resistance was then measured as a function of RF power for the patterned striplines. Comparing our results "before" and "after" the patterning process directly clarifies whether the patterning contributes to the power dependence of the microwave surface resistance observed for YBCO thin films.

A. Sapphire Dielectric Resonator

We have designed a sapphire dielectric resonator, shown in Fig. 3, to measure the microwave surface resistance and especially the power dependence of unpatterned YBCO thin films. The resonator incorporates some unique features, described below, that allow high-power measurements to be carried out without heating the sample via dissipated power. Fig. 4 is a cutaway view of the dielectric resonator.

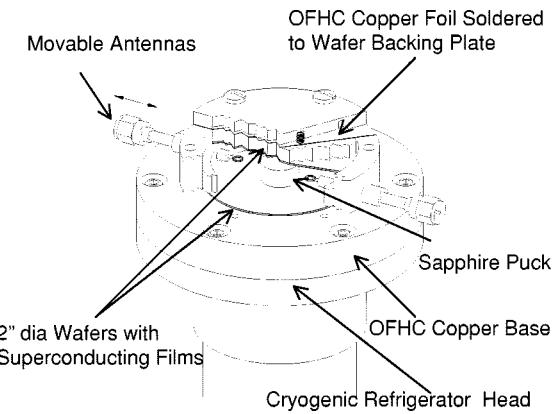


Fig. 4. Cutaway view of the dielectric resonator.

The resonator is made from a 0.5-in-diameter and 0.25-in-high cylindrical sapphire puck that is grounded by two 2-in-diameter YBCO wafers (see left-hand side of Fig. 2). The resonator has fixed output coupling and *in-situ*-adjustable input coupling to ensure critical input coupling (no reflection at the input end) for high-power measurements. The resonator is packaged in an oxygen-free copper case, as shown in Fig. 3. Special thermal contacts were designed to avoid heating problems for high-power experiments. A copper pressure plate was employed on top of the upper YBCO wafer. Springs were used (as shown in Fig. 3) to ensure that the pressure on the YBCO is independent of temperature. A gold-plated copper foil was soldered onto the copper pressure plate to enhance thermal conduction to the copper case from the top YBCO film, which was more likely to be affected by heating than the bottom wafer that was anchored to the copper base plate. Thermal-conducting grease was applied between the sapphire puck and the two grounding wafers. The whole package was operated in a vacuum environment in a cryocooler with the bottom plate bolted to the cold finger with an indium foil for thermal contact. A temperature sensor and a 25Ω heater were mounted on the copper case of the resonator with indium foil to monitor and control the temperature.

The sapphire dielectric resonator was operated at the TE_{011} mode for which the center frequency was 10.7 GHz. The loaded quality factor Q_L , reflection (S_{11} , S_{22}), and transmission (S_{21}) coefficients were measured as a function of input power and temperature. The input coupling loop was tuned *in situ* to maintain critical coupling at each temperature and input power level. Critical coupling at the input maximizes the circulating power and RF magnetic field in the resonator. The output coupling loop was fixed and weakly coupled during each measurement. The unloaded quality factor Q_0 was obtained from the measured S parameters and Q_L , and the surface resistance was deduced from $R_S = G/Q_0$, where G is the calculated geometric factor of the resonator [3]. The results for R_S are presented as a function of peak magnetic field in the resonator. The R_S measured by this method is the average of R_S in the top and bottom YBCO films.

The Q_L was measured using a standard frequency-domain 3-dB-bandwidth method at low input powers where the Q is independent of power. At higher input power levels, a time-domain method was employed to reduce heating effects. In this

method, a continuous wave (CW) microwave pulse with enough duration to fully charge the resonator was sent into the resonator. After the input pulse is turned off, we can calculate Q_L from the decay rate of the output signal that is proportional to $\exp[-\omega t/Q_L]$. By use of the time-domain method with the special thermal design, the R_S could be measured without heating problems for input powers up to 40 dBm, which corresponds to an RF peak magnetic field of ≥ 100 Oe. Surface resistance measurements on two pairs of unpatterned YBCO films were carried out for temperatures in the range of 30–80 K.

In the analysis of the experimental data, we have, as is usual, treated the losses of the YBCO superconducting ground planes as a perturbation that does not affect the field or current distribution, while ignoring the losses due to the sapphire puck itself and the copper case. The assumption that only the YBCO films contribute to the power loss is expected to be valid for the following reasons. A good-quality sapphire crystal is almost lossless at the cryogenic temperature where we operated since the $\tan \delta$ (loss tangent) is estimated [3], [4] to be on the order of 10^{-9} . For YBCO films, a Q_0 of about 10^6 is observed at low temperatures. A pair of 2-in-diameter Nb films have yielded Q_0 values greater than 5×10^6 . That the Nb films gave a higher Q than those of YBCO indicates that the loss in the sapphire puck is negligible compared to that of the YBCO films. We estimated that the loss in the copper case is very small and yields a Q greater than 2.5×10^8 , much higher than that of the YBCO films.

B. stripline Resonator

After the microwave surface resistance of the unpatterned YBCO films was measured with the sapphire dielectric resonator, the films were patterned, and stripline resonators were made. A standard patterning process with wet chemical etching was employed. As shown in Fig. 2, each 2-in wafer was made into four striplines and four ground planes. One piece from each of the top and bottom YBCO wafers used with the dielectric resonator in Fig. 3 was measured. A description of the stripline resonator used here can be found in detail in [5] and [6]. Similar to the dielectric-resonator method, the loaded quality factor Q_L was measured for the stripline as a function of microwave input power up to 35 dBm, corresponding to an RF peak magnetic field of 1000 Oe in the resonator. One advantage of the stripline resonator is that the R_S at different overtone frequencies can be easily measured. By measuring overtones, we can measure the Q at frequencies close to that of the dielectric resonator even though the fundamental resonance of the stripline resonator is 1.5 GHz.

III. EXPERIMENTAL RESULTS

R_S as a function of the RF peak magnetic field H_{\max} at different temperatures was measured for two pairs of unpatterned YBCO films, denoted as pairs 1 and 2 (see Fig. 3). The results are shown in Fig. 5. For pair 1, no nonlinearity in R_S of the unpatterned wafers was observed up to 80 K even at +40 dBm, the maximum available power, and corresponding to H_{\max} values up to 200 Oe. As mentioned above, R_S obtained for the unpatterned wafers is an average surface resistance of the pair of

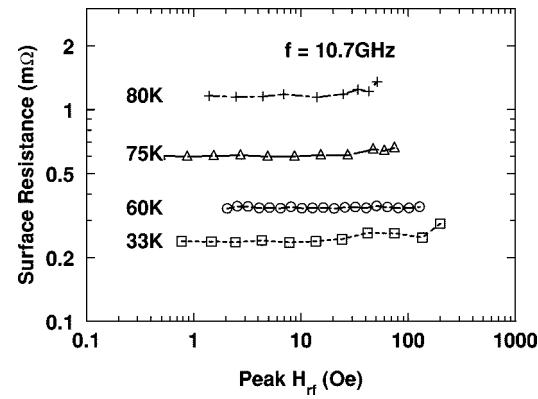


Fig. 5. R_S versus RF peak magnetic field (H_{\max}) for the unpatterned films (pair 1) for various temperatures.

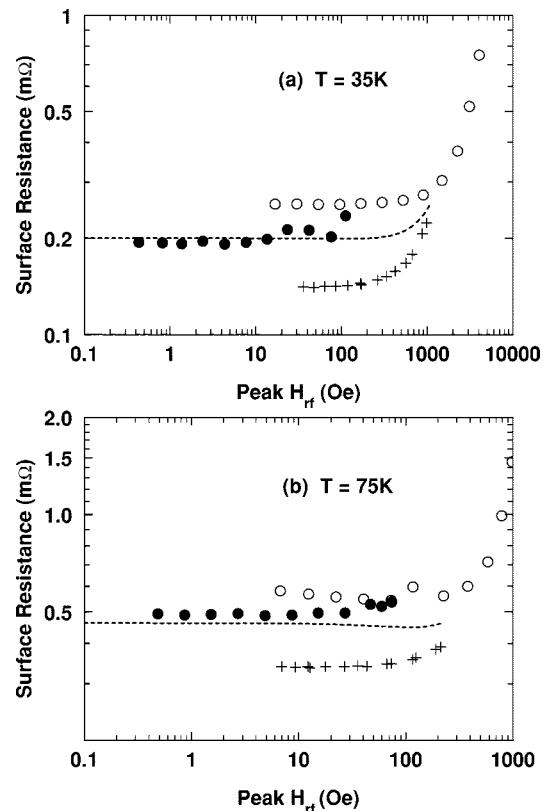


Fig. 6. R_S versus RF peak magnetic field (H_{\max}) for both unpatterned and patterned films (pair 1) at: (a) 35 and (b) 75 K. The solid circles represent data of the unpatterned films, the open circles and crosses represent data of the patterned films from the top and bottom wafers, respectively, and the dashed line represents the average R_S of patterned films from the top and bottom wafers.

films. Fig. 6(a) compares R_S of the unpatterned and patterned films at 35 K for pair 1. The open circles represent the R_S of the patterned film from the top wafer measured in the dielectric resonator, and the crosses denote the R_S of the patterned film from the bottom wafer. The average of those two curves (dashed line) agrees with the R_S of the unpatterned wafers very well and suggests that there is no nonlinearity for H_{\max} up to 500 Oe. Fig. 6(b) shows the results at 75 K for pair 1. For the case of stripline resonators, because of package modes interfering with some of the overtone modes, the R_S could not be measured at the mode closest in frequency to that of the dielectric resonator.

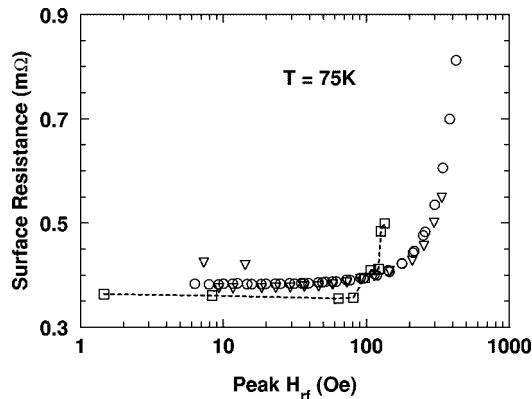


Fig. 7. R_S versus RF peak magnetic field for both unpatterned wafers 1 and 2 and the patterned films (pair 2) at 75 K. The squares represent data of the unpatterned films and the circles and the triangles represent data of the patterned films from the top and bottom wafers, respectively.

Therefore, R_S was measured at the closest frequencies possible. The results for R_S were then scaled assuming $R_S \propto \omega^2$. For pair 1, the R_S of the unpatterned films was measured at 10.7 GHz, and the R_S of the two patterned films was measured at 12 and 7.5 GHz.

From the results in Fig. 6, we conclude that, for pair 1, no degradation in the residual surface resistance was observed in the patterned stripline films up to a H_{\max} of ~ 200 Oe. No power dependence was observed up to the maximum input power available for the unpatterned films, and no effect of patterning on the power handling of YBCO films was found either at 35 or 75 K for pair 1.

We grew another pair of 2-in-diameter YBCO wafers, i.e., pair 2, with a different deposition temperature with the intention to decrease the power handling of the microwave surface resistance. For pair 2 at 35 K, no power dependence of the R_S was observed in the dielectric resonator up to the maximum input power, similar to the results obtained for pair 1. However, at $T = 75$ K, a nonlinearity in the R_S was observed above $H_{\max} \sim 100$ Oe. Results for the patterned films are shown together with that of the unpatterned films in Fig. 7. In this case, R_S was measured at 7.5 GHz for both patterned films in the stripline resonator. The measured residual surface resistance of the unpatterned and patterned films agrees to within 10%. The $R_S(H_{\max})$ of the unpatterned films actually turns up at a somewhat lower H_{\max} than that of the patterned films in the stripline resonator. The apparently better power handling of the stripline resonator can be explained using the same surface impedance by a simple model introduced below. The H_{\max} is the RF peak magnetic field in the two types of resonators, but they have very different field distributions. In the following section, we use the different current/field profiles for both the sapphire dielectric and stripline resonator to model the measured power dependence of the unpatterned and patterned films.

IV. MODEL

The distribution of currents in the films for the dielectric and stripline resonators are different, as shown in Fig. 8. For the dielectric resonator, with a film diameter much larger than the diameter of the sapphire puck so that the edge effects can be

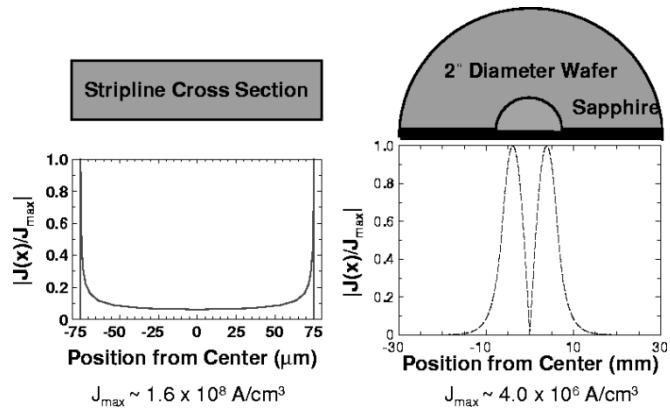


Fig. 8. Current distributions of both the stripline resonator (left-hand side) and the dielectric (sapphire) resonator (right-hand side).

ignored, the current density \vec{J}_{rf} is in the ϕ -direction and has a dependence on radius given by [3], [7]

$$J_{\text{rf}}(r) = \frac{H_{\text{rf}}(r)}{\lambda_0} = \begin{cases} A \frac{\beta}{\xi_1 \lambda_0} J_1(\xi_1 r), & \text{for } 0 < r < a \\ A \frac{\beta}{\lambda_0 \xi_2} \frac{J_0(\xi_1 a)}{K_0(\xi_2 a)} K_1(\xi_2 r), & \text{for } a < r < R \end{cases} \quad (3)$$

where J_0 , J_1 , K_0 , and K_1 are various Bessel functions, β , ξ_1 , and ξ_2 are constants determined by the geometry of the resonator, a is the radius of the sapphire puck, and R is the radius of the superconducting films. The current density thus peaks near the center of the film, as shown in Fig. 8. For the stripline resonator, the current density \vec{J}_{rf} has been calculated numerically in [8]. For the purpose of simplicity in the calculation, we approximated $J_{\text{rf}}(x)$ with the following analytical form [9]:

$$J_{\text{rf}}(x) = \begin{cases} J_{\text{rf}}(0) \left[1 - \left(\frac{2x}{w} \right)^2 \right]^{-(1/2)}, & x \ll w \\ J_{\text{rf}}(0) \left(\frac{1.165}{\lambda_0} \right) (wb)^{1/2} \\ \cdot \exp \left(-\frac{w/2 - |x|}{\lambda_0^2} b \right), & x \approx w \end{cases} \quad (4)$$

where w and b are, respectively, the width and thickness of the film. This analytical approximation agrees with the numerically calculated current distribution to within 5% in our case. Thus, $J_{\text{rf}}(x)$ peaks sharply at the edges of the patterned film for the stripline resonator. For the dielectric resonator, as is obvious in (3), $J_{\text{rf}}(x)$ is related directly to the RF peak magnetic field H_{\max} . For the stripline resonator, H_{\max} can be calculated numerically from the current distribution in the stripline [8]. For the same H_{\max} in the dielectric and stripline resonators, the portion of the film carrying a high current density is larger for the dielectric resonator due to the broader peak in the $J_{\text{rf}}(r)$ distribution of the dielectric resonator. Therefore, an apparently better power handling in the stripline resonator is not surprising.

The quality factors Q_0 (H_{\max}) of both resonators have been calculated as a function of RF peak magnetic field using the

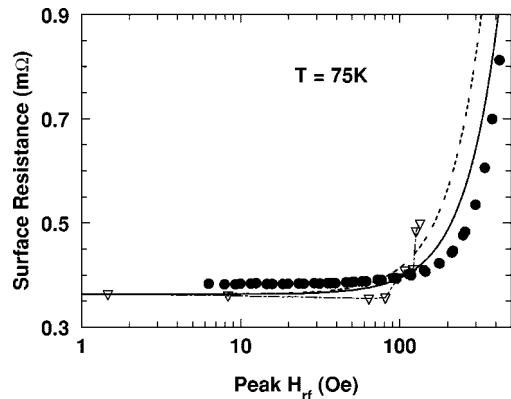


Fig. 9. Modeled and measured R_S versus RF peak magnetic field for both the dielectric and stripline resonators. The triangles represent the measured R_S for the dielectric resonator, the circles represent the measured R_S for the stripline resonator, the dashed line represents the modeled R_S for the dielectric resonator, and the solid line represents the modeled R_S for the stripline resonator.

current distributions given above. With the assumption for ρ and λ , given by (1) and (2), and

$$Q_0 = \omega \frac{W_{\text{stored}}}{P_{\text{diss}}} \quad (5)$$

where W_{stored} is the total energy stored and P_{diss} is the power dissipated in the resonator. The parameters ρ_0 and λ_0 were taken from experimentally measured values $\rho_0 = 7.2 \times 10^{-11} \Omega\text{m}$, $\lambda_0 = 0.2 \mu\text{m}$, which fit the low-field linear part of R_S and the temperature dependence of the resonant frequency. The non-linear parameters of resistivity and penetration depth used in the calculations were $\rho_2 = 1.0 \times 10^{-35} \Omega\text{m}^5/\text{A}^2$ and $\lambda_2 = 2.5 \times 10^{-29} \text{m}^5/\text{A}^2$. These parameters were taken to fit the R_S obtained from the dielectric resonator measurements. The unloaded quality factor for the stripline resonator was then calculated with the same set of parameters. At low RF field, calculated values of Q_0 of 7×10^5 and 6000, respectively, were obtained for the dielectric and stripline resonators, and these values are consistent with the measured values. The modeled results also show that the power dependence of R_S for both the dielectric and stripline resonators is quantitatively consistent with the measured power dependence for both resonators. The modeled R_S of the dielectric resonator turns up at a smaller value of H_{max} than that of the stripline resonator, which agrees well with the experimental result, as shown in Fig. 9.

V. CONCLUSIONS AND DISCUSSION

We have measured the microwave surface resistance of the *same* YBCO thin films, before and after patterning, using sapphire dielectric and stripline resonators. A phenomenological model of the R_S (H_{max}) in the two cases is presented. Based on this model, the calculated results fit the experimental data well in both cases using the same materials parameters. Therefore, we conclude that our results are consistent with no damage or degradation of the power dependence of the microwave surface resistance due to the patterning of the films. The procedure described in this paper can also be used to test other patterning processes such as ion beam etching.

ACKNOWLEDGMENT

The authors express their gratitude to R. Konieczka, Lincoln Laboratory, Lexington, MA, J. Aversa, Lincoln Laboratory, Lexington, MA, D. Baker, Lincoln Laboratory, Lexington, MA, and E. Macedo, Lincoln Laboratory, Lexington, MA, for applying their tireless efforts and effective skills to the preparation of the devices used in this paper, and to P. Murphy, Lincoln Laboratory, Lexington, MA, for operation of the SEM.

REFERENCES

- [1] A. C. Westerheim, P. C. McIntyre, S. N. Basu, D. Bhatt, L. S. Yu-Jahnes, A. C. Anderson, and M. J. Cima, "Comparison of the surface morphology and microstructure of *in situ* and *ex situ* derived $\text{YBa}_2\text{Cu}_3\text{O}_{7-\alpha}$ thin films," *J. Electron. Mater.*, vol. 22, pp. 1113–1120, 1993.
- [2] A. C. Anderson, R. L. Slattery, D. E. Oates, and L. S. Yu-Jahnes, "Cylindrical magnetron deposition of high-quality high-temperature superconductive thin films," *Lincoln Lab., Lexington, MA, Solid State Res. Quarterly Tech. Rep.*, pp. 31–33, vol. 2, 1993.
- [3] Z. Y. Shen, C. Wilker, P. Pang, W. L. Holstein, D. Face, and D. J. Kountz, "High T_c superconductor-sapphire microwave resonator with extremely high Q -values up to 90 K," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2424–2431, Dec. 1992.
- [4] D. G. Blair and A. M. Sanson, "High Q tunable sapphire loaded cavity resonator for cryogenic operation," *Cryogenics*, vol. 29, pp. 1045–1049, 1989.
- [5] D. E. Oates, A. C. Anderson, and P. M. Mankiewich, "Measurements of the surface resistance of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\alpha}$ thin films in stripline resonators," *J. Superconduct.*, vol. 3, pp. 251–259, 1990.
- [6] D. E. Oates, P. P. Nguyen, G. Dresselhaus, M. S. Dresselhaus, C. W. Lam, and S. M. Ali, "Measurements and modeling of linear and non-linear effects in striplines," *J. Superconduct.*, pp. 361–369, 1992.
- [7] D. Kajfez and P. Guillon, *Dielectric Resonators*. Norwood, MA: Artech House, 1986.
- [8] D. M. Sheen, S. M. Ali, D. E. Oates, R. S. Withers, and J. A. Kong, "Current distribution, resistance and inductance for superconducting strip transmission lines," *IEEE Trans. Appl. Superconduct.*, vol. 1, pp. 108–115, June 1991.
- [9] T. van Duzer and C. W. Turner, *Principles of Superconductive Devices and Circuits*. Amsterdam, The Netherlands: Elsevier, 1981.



Hao Xin received the B.S. degree in physics and mathematics from the University of Massachusetts at Dartmouth, in 1995, and is currently working toward the Ph.D. degree in physics at the Massachusetts Institute of Technology, Cambridge.

His research interests are in the area of fundamental properties of superconductors at microwave frequencies and the application of superconducting devices in microwave engineering.



Daniel E. Oates (M'87) received the B.A. degree in physics from Yale University, New Haven, CT, and the Ph.D. degree in physics from the Massachusetts Institute of Technology, Cambridge.

He held an Alexander von Humboldt Fellowship at the University of Bonn, Bonn, Germany. Since 1978, he has been with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, where his research has included investigations of surface-acoustic-wave and bulk-wave devices. Since 1988, his primary research interests have been in superconducting electronics, especially applications in frequency control and microwave-frequency analog signal processing. Motivated by the applications of superconductors, he has investigated the fundamental properties of superconductors at microwave frequencies and at high microwave power levels. These investigations have included both high- T_c and low- T_c materials.

been in superconducting electronics, especially applications in frequency control and microwave-frequency analog signal processing. Motivated by the applications of superconductors, he has investigated the fundamental properties of superconductors at microwave frequencies and at high microwave power levels. These investigations have included both high- T_c and low- T_c materials.

A. C. Anderson, photograph and biography not available at time of publication. **G. Dresselhaus**, photograph and biography not available at time of publication.

R. L. Slattery, photograph and biography not available at time of publication. **M. S. Dresselhaus**, photograph and biography not available at time of publication.