Invited Paper

Microwave Device Applications and High Frequency Electrodynamics of High Temperature Superconductors

Dong Ho Wu[1], Mark Santer[1], James C. Booth[1†], Julia Phillips[2], and Steven M. Anlage[1]

[1] *Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, MD 20742-4111*

[2] *Sandia National Laboratories, Albuquerque, NM 87185-5800*

† *Present address: NIST, Boulder, Co 80303*

Despite the numerous advantages of microwave passive devices using high temperature superconductors, use of all-HTSC microwave devices has been limited to weak power signal processing due to the limitations in power handling capabilities of the materials. Moreover, practical applications of the HTSC microwave devices have been focused on frequencies below 10 GHz. These technical barriers can be overcome by understanding the detailed high frequency electrodynamic properties of high temperature superconductors. Our experiments, carried out on samples with various degrees of quality over a broad dynamic range of microwave power, frequency, external magnetic fields and temperatures, suggests that for the improvement of the power handling capability and an increase of the frequency application range, the devices made of HTSC materials should have fewer Josephson junctions and increased materials homogeneity.

Keywords: high temperature superconductors, surface impedance, microwave power dependence, microwave field dependence, dc field dependence, frequency dependence

Among various applications using high temperature superconductors, superconducting microwave passive devices may be the best candidate for the first commercialization. Because of their low surface resistance and capacity for relatively large current density, high temperature superconductors (HTSC) have been extensively explored for microwave passive device applications. Prototype HTSC microwave devices have exhibited a smaller insertion loss, smaller size and higher performance in comparison with their conventional counterparts. [1] Despite these advantages, presently the use of all high temperature superconducting microwave devices has been limited to relatively weak signal processing due to the severe limitation in power handling capabilities of the devices. [1,2] Besides these power handling problem, which is related to nonlinearity and intermodulation problems [3,4], the operating frequencies of the practical HTSC devices also have been limited to frequencies below 10 GHz. While detailed and systematic studies in materials processing, circuit design, and even the pairing symmetry of the superconducting state must be carried out to provide clues to understand the presently not-so-well-understood problems related to the power handling capability, in this paper we will discuss our preliminary experimental results on microwave power, field, and frequency dependences of the surface impedance.

We have studied a few different $YBa_2Cu_3O_{7-\delta}$ (YBCO) samples including c-axis laser-ablated YBCO films (thin films #1 and #2) on $LaAlO_3$ with thickness ranging from 2000 - 5000 Å, and similar YBCO films (thin film pair #3) made by post-annealed BaF_2 evapora-

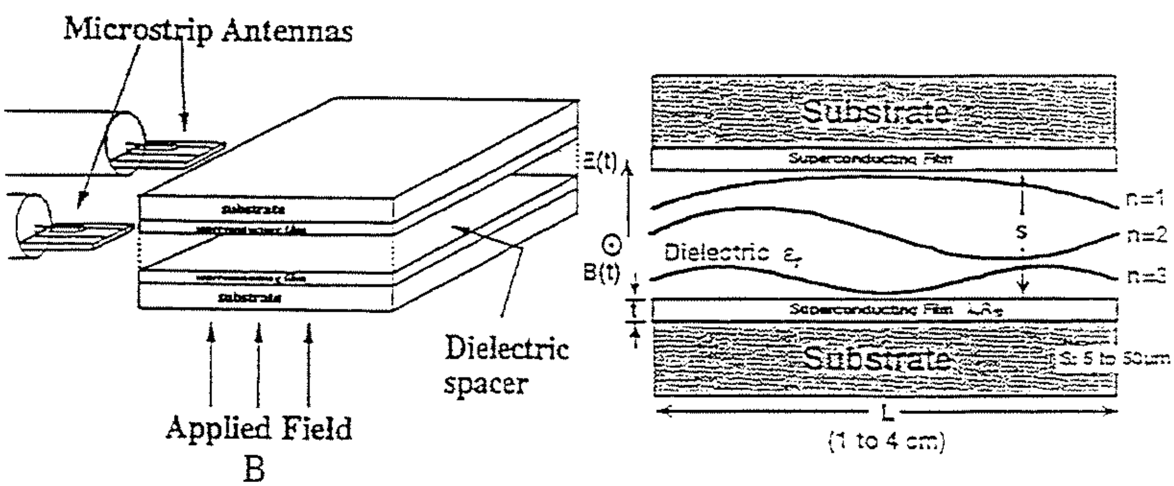

FIG. 1. The parallel plate resonator. Solid sinusoidal lines indicate microwave magnetic field strength.

study both the dc and the microwave field dependences for a HTSC device, we employed the parallel plate resonator (PPR) technique developed by Taber. [6] In brief, as shown in Fig. 1, the parallel plate resonator consists of a (nearly identical) pair of superconducting films separated by a dielectric spacer with dielectric constant ϵ_r and thickness s. The PPR is coupled to two microstrip antennae (a feed and a pick-up antennae) which are connected to a HP 8510C vector network analyzer through a pair of semi-rigid coaxial transmission lines. The coaxial transmission lines are approximately 1.6 m long to place the PPR at the center of a Nb-Ti superconducting magnet for a dc field dependence study. Initial measurements are carried out with zero external dc magnetic field. We measure the resonance frequency f_0, the resonance quality factor Q, and the reflection coefficients S_{11} and S_{22} with an effective power at the PPR ramping from −15 dBm to 15 dBm at each fixed temperature. Typical results for Q and frequency shift for film #3 with the microwave power variation are shown in Fig. 2. We find a considerable variation of Q and the frequency shift despite a relatively small power variation range. Interestingly our data in Fig.2 suggest a discrete change of Q with P_{rf} at $H_{dc} \approx 0$. To examine the electrodynamics in a more systematic manner

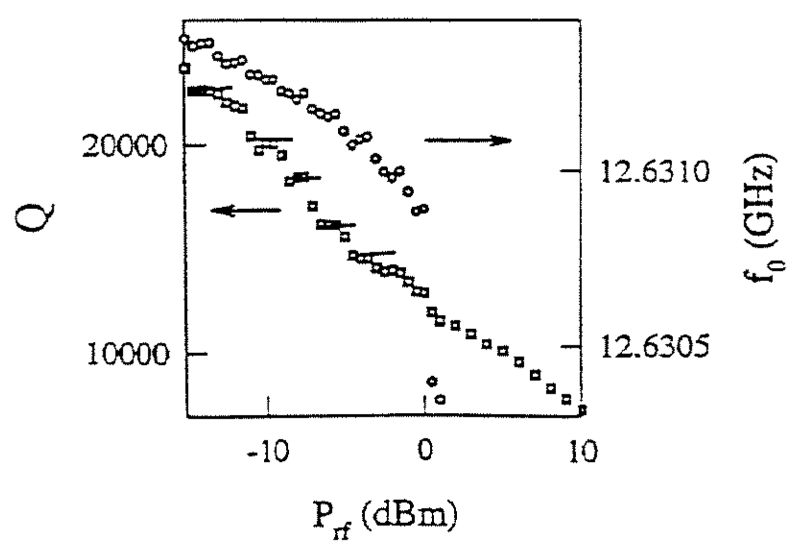

FIG. 2. Q and the resonant frequency vs. P_{rf} at T=4.7K for YBCO film #2.

we carried out similar measurements with finite dc magnetic fields. In the measurements, dc fields are applied parallel to the c-axis (i.e. perpendicular to the film surface). The dc field strength is determined using a Hall probe which is attached near the center of the PPR. The uncertainty in determining of the field strength is less than 1% considering all possible uncertainties due to a possible residual magnetic field trapped in the Nb-Ti superconducting magnet, uncertainty of the Hall probe, and also uncertainty in determining the sample demagnetization factor, as we need to make a correction for the magnetic field $H_{dc}=\aleph H_a$ for this field configuration. Here $\aleph$ is a demagnetization factor and H_a the applied dc magnetic field strength. Also we convert the f_0 and Q into R_s and λ using the relations $f_0 = (nc/2L\sqrt{\epsilon_r})/\sqrt{1+\frac{2\lambda}{s}\coth(t/\lambda)}$ and $R_s = (\pi\mu_0 f_0 s)/Q$. Typical power dependence data of the surface resistance are shown in Fig. 3 for various dc magnetic fields.

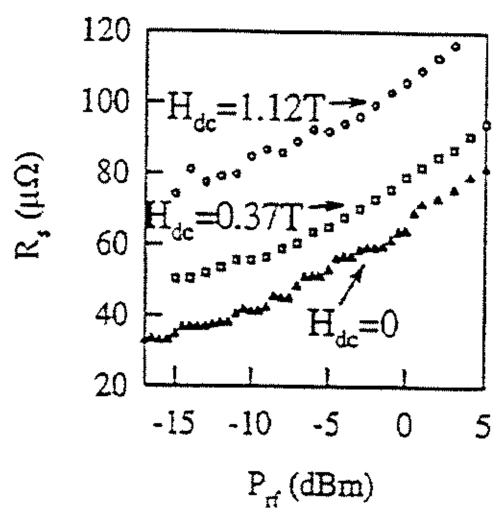

FIG. 3. R_s vs. P_{rf} for H_{dc}=0, H_{dc}=0.37 T, and H_{dc}=1.12 T at T=4.7K and $f_0 \simeq$ 12.63GHz for YBCO film #2.

As was already hinted in Fig. 2, $R_s(P_{rf})$ with H_{dc}=0 shows a discrete variation with P_{rf} which appears qualitatively similar to Shapiro steps. A similar observation has been first made in the BSCCO system by Jacobs et. al., who attributed the behavior to the existence of Josephson junctions in the sample. [3] One can test if the behavior is due to the existence of Josephson junctions by examining the power dependence of the surface resistance under various dc magnetic fields. Josephson junctions can sustain supercurrents as long as the magnetic field strength does not exceed the Josephson junction critical field $B_c^{JJ}=\phi_0/A_{JJ}$. The junction area is given as $A_{JJ}=(2\lambda_L+t)w$ where λ_L is the penetration depth at the Josephson junction, t is the junction length and w is the junction width. Typical YBCO thin films have junction sizes in the range of a few tenths to a few μm^2 and hence a typical Josephson junction critical field is estimated to be a few tens of Oe. Our earlier experiments on samples with large junctions exhibited small B_c^{JJ} and the junctions have been easily broken down even with moderate field strength (a few Oe). [7] Subsequent experiments with improved sample quality revealed the field dependence became substantially smaller, suggesting at least an order of magnitude increase of B_c^{JJ}. [8] For a thin film with junction size smaller than a few Å, we expect the maximum Josephson junction critical field B_c^{JJ-max} can approach a value comparable to the intrinsic lower critical fields (on the order of a few hundred Oe). In any case, if the discrete increase of R_s is due to Josephson junctions, it is expected that the discreteness will disappear at a substantially high field ($H > B_c^{JJ}$). In fact this is what we see in Fig. 3, and hence our data on $R_s(H_{rf})$ at various H_{dc} strongly suggests the existence of the Josephson junctions in our thin films. Also in Fig. 3, we find the surface resistance has less power dependence at higher dc fields. This is because at higher dc field, fewer Josephson junctions can survive and respond to the microwave power.

To compare dissipation at microwave fields and at dc fields, we convert the microwave power into microwave field strength. In this process we consider the maximum microwave field strength, as the maximum microwave field dominates the electrodynamic behavior such as $\lambda(H_{rf})$ and $R_s(H_{rf})$. For the conversion, first we obtain an average microwave field strength from the relation $\langle H_{rf}\rangle = c\sqrt{Q_{unload}P_{ppr}/\omega_0}$ where c is a conversion factor to be determined, Q_{unload} is the unloaded Q, and $\omega_0 = 2\pi f_0$. We estimate the microwave power fed into the PPR using $P_{ppr} = 10^{-3}10^{(p_{in}/10)}\{4\beta_1/(1+\beta_1+\beta_2)^2\}$ where p_{in} is the power input into the PPR in dBm. The coupling constants β_1 and β_2 are obtained from the measured reflection coefficients S_{11} and S_{22}. Once we obtained $\langle H_{rf}\rangle$, we estimate the maximum field strength by considering the field strength distribution over the PPR. For a strip with a film of width w greater than its thickness d, the current density varies as function of location x given as $J_s(x) = J_s(0)[1-(2x/w)^2]^{-1/2}$ near the center of the strip ($x \sim 0$) and $J_s(x) = J_s(\frac{1}{2}w)\exp -[(\frac{1}{2}w - |x|)d/a\lambda^2]$ near the edges ($x \sim \frac{w}{2}$). [9] Here $a \simeq 1$ and the ratio of the current densities at the edge and at the center is given as $J_s(\frac{1}{2}w)/J_s(0) \approx (1.165/\lambda)\sqrt{wd}$. [9] This location-dependent current density yields a large current crowding at the edges. Fig. 4 shows an example of the current crowding at the edges of our PPR. Consequently the rf magnetic field strength is also enhanced near the edge, as the local rf magnetic field is related to the current as $J = H_{rf}/\lambda$. Using the relation $\langle H_{rf}\rangle = \frac{1}{A}\int H_{rf}\, da$ and $J_{max} = J_s(\frac{1}{2}w)$, we estimate the maximum microwave field strength. Here A is the total surface area where induced currents flow.

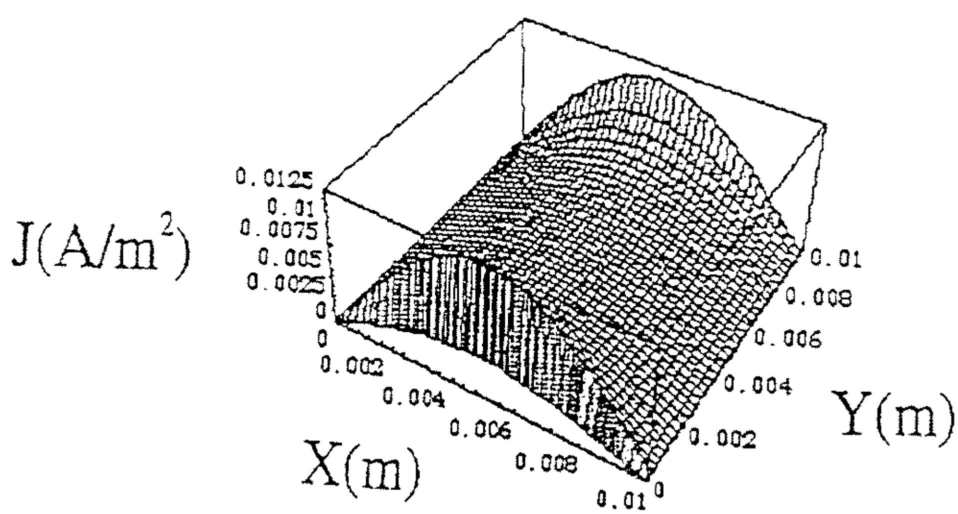

FIG. 4. Calculated current crowding at the edge of PPR.

Now we compare the microwave field dependence results with the dc field dependence. Using the above procedure, we convert our $R_s(P_{rf})$ data into $R_s(H_{rf})$ for another pair of thin films (thin film pair #1) as shown in Fig. 5. For comparison purposes, we display the dc field dependence of the surface resistance, which is obtained from the same pair of thin films (#1), along with $R_s(H_{rf})$ data. In Fig. 5, although one can find a qualitatively similar behavior between $R_s(H_{rf})$ and $R_s(H_{dc})$ which is consistent with earlier published results [2], the surface impedance shows at least an order of magnitude larger field dependence under the microwave field than under the dc field. In other words, H_{rf} causes about an order of magnitude larger dissipation than H_{dc} does. Detailed analysis on this microwave field dependence is underway and will be published elsewhere.

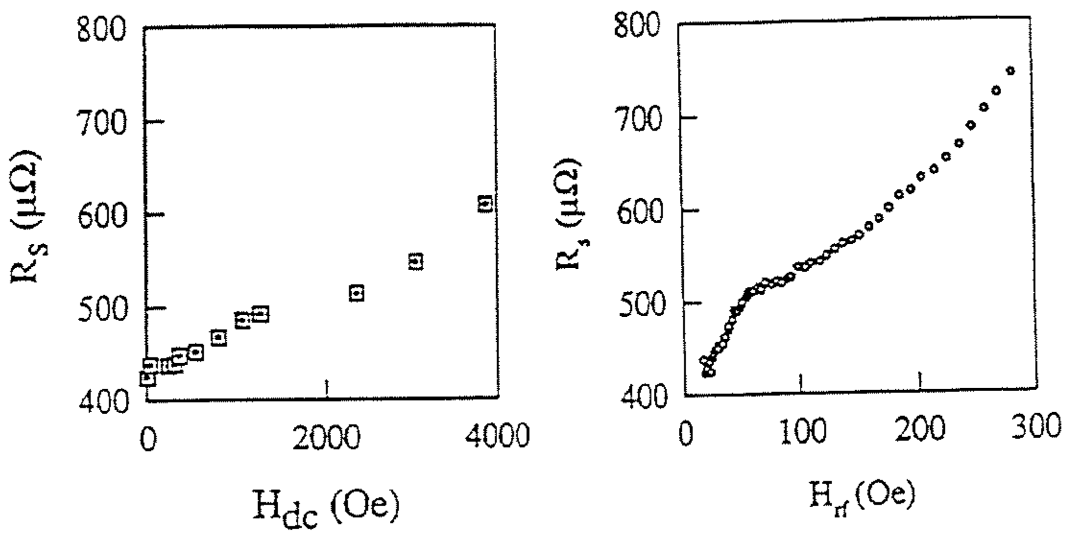

FIG. 5. Field dependence of the surface resistance under the microwave field and the dc magnetic field at T=4.5 K and f_0=9.7 GHz for YBCO film pair #1.

In addition to the field dependence of the surface impedance, we also measured the surface impedance Z_s of YBCO thin films (#2) with a continuous frequency sweep from 45 MHz through 45 GHz as discussed in detail in our earlier publications. [10,11] For a thin film with thickness t_0 less than the penetration depth, the measured surface impedance is given by $Z_s \simeq \tilde{\rho}/t_0$ where $\tilde{\rho}$ $(= \rho_1 + i\rho_2)$ is the complex resistivity. [12] The transition width of ρ_1 at $\sim$ 200 MHz for various thin films are within the range of 1 - 3 K which are typical values for thin films at high frequencies. However it appears that the transition width is much broader than those of high quality single crystals. Using $\tilde{\rho} = 1/(\sigma_1 + i\sigma_2)$, we extract σ_1 and σ_2 which reveal an anomalously large frequency dependence in the frequency range 45 MHz through 45 GHz. In this frequency range, the real part of the complex conductivity is not expected to show a significant frequency dependence, especially at temperatures several degrees below the transition temperature where the frequency dependence due to the fluctuations becomes negligibly small. Also, in contrast to our expectation, data for $T < T_c$ indicate that the lower the temperature, the stronger the frequency dependent conductivity. For a conventional defect-free superconductor, we expect that strongly frequency dependent conductivity appears near the transition temperature due to fluctuations and this fluctuation driven frequency dependence will diminish at temperatures well below the transition temperature, replaced by a weak logarithmic frequency dependence $\sigma_1 \sim \ln \frac{1}{\omega}$. However our data indicate that the trend is opposite as shown in Fig. 6, with σ_1 exhibiting much stronger frequency dependence than the logarithmic dependence at low temperatures.

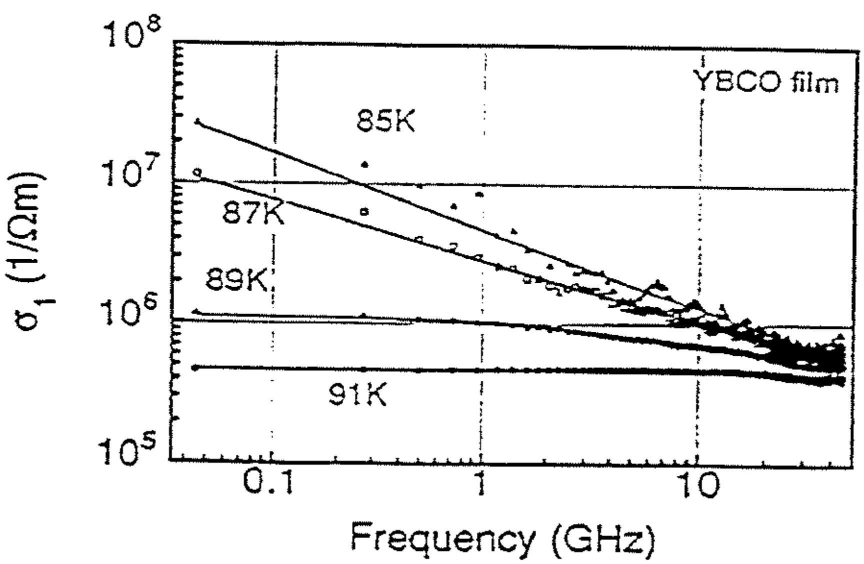

FIG. 6. The frequency dependence of the complex conductivity for film #3 at various temperatures below the transition temperature

The results have been analyzed in terms of the fluctuation effects and the sample inhomogeneity effects [10,11] as both effects can give rise to the frequency dependence of the complex conductivity. The solid lines in Fig. 6 represents $\sigma_1(\omega) = k[\sigma_1^{EM}(\omega) + \sigma_1^F(\omega)]$, where k is a prefactor, $\sigma_1^{EM}(\omega)$ is the real part of the effective conductivity calculated using an effective medium model [13] to account for the sample inhomogeneity, and $\sigma_1^F(\omega)$ is a calculation of the fluctuation conductivity with an effective dimensionality D=3, based on the time dependent Ginzburg-Landau theory [14]. Throughout the fitting, we used the value for k within 0.8 - 1.1 for data at different temperatures and for various samples. For $\sigma_1^{EM}(\omega)$, we used a simple model which the effective medium conductivity is given as $\frac{1}{\sigma^{EM}} = \rho_{eff} = \int_{T_c^{min}}^{T_c^{max}} \frac{g(T_c)}{\sigma(\omega,T,T_c)} dT_c$ with a simple Gaussian distribution function for $g(T_c) = e^{-(T_c-T_{c0})^2/\delta T_c^2}/(T_c^{max} - T_c^{min})$. Here T_c^{max} and T_c^{min} are the maximum and the minimum T_c due to the distribution of transition temperatures in the different superconducting grains. For the frequency- and temperature-dependent complex conductivity, we use $\sigma(\omega, T, T_c) = \sigma_n(\omega, T)\frac{\tau(T)X_n}{\tau(T_c)} + i\frac{1}{\mu_0\omega\lambda^2}$ where $\sigma_n(\omega, T)$ is the Drude model normal state conductivity, τ is the quasiparticle relaxation time given as $\tau(T) \simeq 2 \times 10^{-10} e^{-T/12}$, and λ is the penetration depth. The nomal fluid density X_n is given by $X_n = (T/T_c)^2$. [15] To fit our data we used the transition width $\delta T_c \approx 2$ K, $T_c^{max} \approx$ 91 K, $T_c^{min} \approx 86$ K, $T_{c0} \simeq 88.5$ K, and $\lambda(0) \simeq 2000\AA$. Within the models we considered above, we find that at temperatures near the transition temperature, the fluctuation effects dominate the frequency dependence. As temperature decreases several degrees below the transition temperature, this frequency dependence driven by the fluctuations diminishes and the inhomogeneity effects dominate the frequency dependence. Thus our data in Fig. 6, which shows stronger frequency dependence at lower temperatures, possibly suggests that our thin film contain a considerable amount of inhomogeneous material.

In this study we have briefly examined i) the microwave power dependence of the surface impedance to understand the power handling capability, ii) the field dependence of the microwave fields and the dc fields, and iii) the frequency dependence of the cuprate superconducting microwave devices. We find that the grain boundary weak-links coupled by moderate size Josephson junctions can be broken down even at moderate fields and hence cannot handle large signals. This is especially true for a superconducting device with high Q as the maximum microwave field strength in the device can reach far above the Josephson junction critical field even for a microwave power below 15 dBm. Our data also suggest that despite the qualitative similarity in the field dependence behavior of the surface resistance under the microwave field and under the dc magnetic field, the surface impedance under the microwave field has at least an order of magnitude stronger field dependence than that of the dc field. In addition to this field dependence study, another type of measurement with frequency variation revealed that in general, the existence of materials inhomogeneity increases the power dissipation and also gives rise to an excessive frequency dependence of the microwave conductivity at temperatures well below the transition temperature.

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