Electromagnetics in High-T_c Superconductors

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***Abstract*— The behavior of electromagnetic fields in high-T_c superconductors (HTS's) is studied in order to examine their effects in classical electromagnetic boundary value problems. It is shown that an HTS can not be simply treated as a low loss conductor and boundary conditions of HTS's can not be considered as perfect conducting boundaries like conventional treatments. The electromagnetics of HTS are investigated in terms of complex conductivity, surface impedance with applied magnetic fields, and computational electrodynamics using the new proposed model in [1].**

I. Introduction

BECAUSE superconductors have a very small resistance, they have possible applications, e.g., also in microwave electronics and engineering. The discovery of high-T_c superconductors (HTS's) has fundamentally changed the prospects for applications of superconductive electronics. To effectively use HTS's in microwave engineering, computer simulation is needed to analyze and design superconducting devices, components, and circuits. For this purpose, the electromagnetics of HTS's must be clearly understood.

Therefore, HTS's in this paper are studied from an electromagnetic point of view. The discussions given in this paper do not seek to find the physics of HTS's, but rather to use a newly developed model of HTS's [1] in macroscopic electrodynamics. Complex conductivity, the dependence of the surface resistance external magnetic fields, and computational electromagnetics are investigated in details.

To study the electrical behavior of HTS's, a suitable model of HTS is needed. There are two conventional models successfully applied to conventional low temperature superconductors, Bardeen, Cooper, and Schreiffer (BCS) theory and two-fluid model [5], [6]. Because there are no suitable models for HTS's, these two models are often simply applied to HTS's. But the theoretically calculated results from these two models deviate seriously from measured data (see, e.g., [1], [4] and references therein).

A. BCS Theory

BCS theory is a microscopic model, which works well for low-T_c superconductors if weak-coupling is assumed.

The conductivity of superconductors is a complex quantity $\sigma = \sigma_1 - j\sigma_2$ and σ_1 is given, e.g., in [7] by

$$\frac{\sigma_1}{\sigma_n} = \frac{2\Delta}{k_B T} e^{-(\Delta/k_B T)} \ln\left(\frac{\Delta}{\hbar\omega}\right), \quad (\hbar\omega \ll \Delta) \tag{1}$$

Manuscript received April 9, 1995; revised December 18, 1995. J.-G. Ma was supported by Deutscher Akademischer Austauschdienst.

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Publisher Item Identifier S 0018-9480(96)02335-6.

and the surface resistance according to the BCS theory is [7]

$$R_s = \frac{1}{2}\mu_o^2 \sigma_n \lambda^3(T) \frac{2\Delta}{k_B T} e^{-(\Delta/k_B T)} \omega^2 \ln\left(\frac{\Delta}{\hbar\omega}\right) \tag{2}$$

where σ_n is the conductivity of material in normal state, and $\lambda(T)$ is the magnetic penetration depth, k_B is the Boltzmann constant, and 2Δ is the energy gap.

From (1) it is known that the predicted frequency dependence of σ_1 is of the form $\ln(1/\omega)$, and σ_1 is less than σ_n if temperature is far below T_c. Although it is not clear whether the superconducting gap in HTS's like YBCO follows the BCS theory, many physicists believe that this theory is a suitable model if the strong-coupling for HTS's is assumed [2]. But actual research indicates in [8, pp. 425–426] that "Simple BCS theory faces a major difficulty: if the electron-phonon interaction is strong enough to produce a T_c around 100 K, then it should be strong enough to make the putative superconducting phase unstable against a transition to some other crystal structure." Therefore [5] states, "it is interesting to observe that the BCS theory may not be adequate in explaining the phenomena of high-temperature superconductivity."

B. Conventional Two-Fluid Model

This model is a macroscopic model proposed by Gorter *et al.* [5], [6]. For the intermediate temperature range, $0 < T < T_c$, both two carriers, superelectrons with density n_s and normal electrons with density n_n, exist simultaneously and $n = n_s + n_n$. Here n is the total density and

$$\frac{n_n}{n} = f(t), \quad \frac{n_s}{n} = 1 - f(t) \quad \text{with} \quad t = \frac{T}{T_c}, \tag{3}$$

where $f(t) \leq 1$ is a function of the temperature T. There are many expressions for $f(t)$ given in the literature, e.g., the Gorter–Casimir expression, $f(t) = t^4$ in [5] and [6]. Qualitatively, it is imagined in the two-fluid model that the gas of normal electrons and the gas of superelectrons do not interact with each other at a given temperature $T < T_c$ [5] as shown in Fig. 1.

The total current density is the sum of the supercurrent density $\boldsymbol{J}_s$ and the normal current density $\boldsymbol{J}_n$

$$\boldsymbol{J} = \boldsymbol{J}_s + \boldsymbol{J}_n. \tag{4}$$

According to this model, the real and imaginary parts of the complex conductivity of HTS's are given as [5]–[7]

$$\sigma_1 = \sigma_n f(t), \tag{5}$$

$$\sigma_2 = \frac{1}{\omega\mu_o\lambda^2} \tag{6}$$

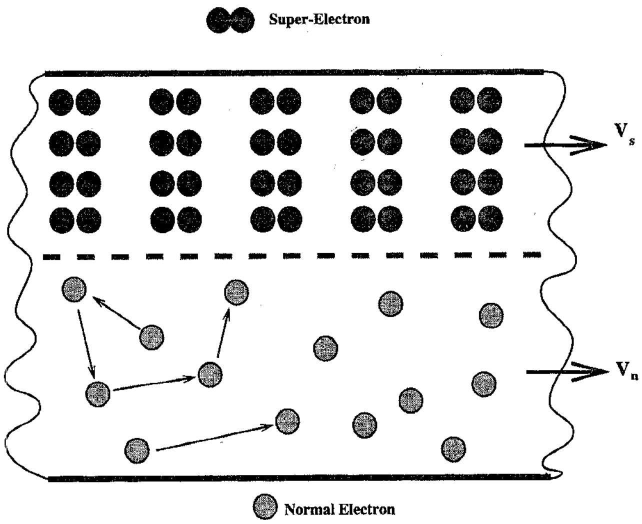

Fig. 1. Two-fluid model.

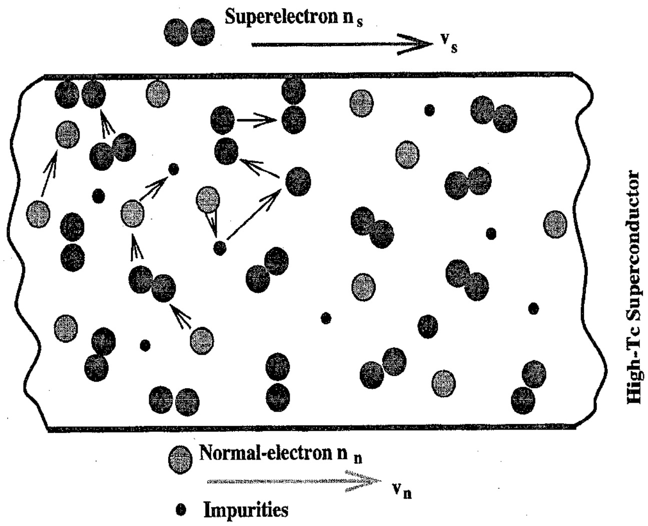

Fig. 2. New two-fluid model.

where the assumption $\omega\tau_n \ll 1$ is used for a HTS at temperature far below T_c.

It is known from (5) that the real part σ_1 of conductivity for HTS's is always less than that in the normal conducting state σ_n, and it is independent of the operating frequency, too. But Bhasin *et al.* in [9] and Piel *et al.* in [10] indicated that for HTS's like YBCO the real part of the conductivity σ_1 is very large compared to that of the normal state σ_n. The measured data given by Nuss *et al.* in [11] indicate that the real part of the conductivity for HTS YBCO is also a function of the driving frequency and it is larger than σ_n, too. Both (1) and (5) can not interpret and simulate the phenomena.

As mentioned above, the predicted results of σ_1 by both the BCS theory and conventional two-fluid model show big deviations from the measured data. Therefore, as a result, also the predicted surface resistance does not agree with measured values (see, e.g., [1] and the references therein).

C. New Phenomenological Model of HTS's

Because the results of classical models like the BCS theory and the two-fluid model deviate from experimental results for HTS's as discussed above, it is desired that a more accurate model is available particularly for applications in microwave engineering. The main assumption in the two-fluid model is that the superelectrons are scattering free and lossless. Orlando *et al.* in [5] indicates "the individual electrons of a Cooper pair still scatter." The actual research given by Mei *et al.* in [12] shows that "the superfluid cannot be truly lossless to an ac field" and the results of the two-fluid model do not obey the generally accepted causal Kramers–Kronig relation. Impurities can also affect the behavior of superelectrons [6]. In the conventional two-fluid model these effects are not considered. May be this is the reason that the theoretical results obtained from the two-fluid model do not agree with experimental results of HTS's.

Recently, a new phenomenological model of HTS's has been proposed [1]. In this new model the idea of two current carriers like in the two-fluid model is used, but the effects mentioned above are considered as shown in Fig. 2. τ_s is introduced as a model parameter, which describes the "collective" effects as mentioned above and can be treated as a "effective relaxation time constant" of HTS's.

II. Electromagnetics of HTS's

In this section using the new phenomenological model of HTS's, the electromagnetic properties of HTS's will be discussed in detail.

A. Conductivity of HTS's

Assuming the local relation of Ohm's law is still valid like in the two-fluid model. Using (4) the conductivity $\sigma = \sigma_1 - j\sigma_2$ of HTS's can be expressed as [1]

$$\sigma_1 = \sigma_n f(t) + \frac{\sigma_2}{\omega\tau_s}, \tag{7}$$

$$\sigma_2 = \frac{n_s q^2}{m\omega}\frac{1}{1+1/(\omega\tau_s)^2} \approx \frac{1}{\omega\mu_o\lambda^2} \tag{8}$$

with the effective penetration depth

$$\lambda = \lambda_L\sqrt{1+1/(\omega\tau_s)^2} \tag{9}$$

where λ_L is the London penetration depth defined in the two-fluid model [5]–[7]. It is clear that if there are some impurities, parameter τ_s will vary, then the magnetic penetration depth will also vary unlike the two-fluid model in which magnetic penetration depth is not dependent on impurities. Here the generally accepted approximation $\omega\tau_n \ll 1$ [5]–[7] has been used. However, the penetration depth is approximately independent of frequency in the microwave range [5]–[7], therefore we have [1]

$$\omega\tau_s = \alpha(T). \tag{10}$$

Now $\alpha(T)$ is only a function of the driving temperature. Because the imaginary part of the conductivity σ_2 of HTS's is frequency dependent with the form $\sigma_2 \sim f^{-1}$, from (7) it can be seen that the real part of the conductivity σ_1 of HTS's is also

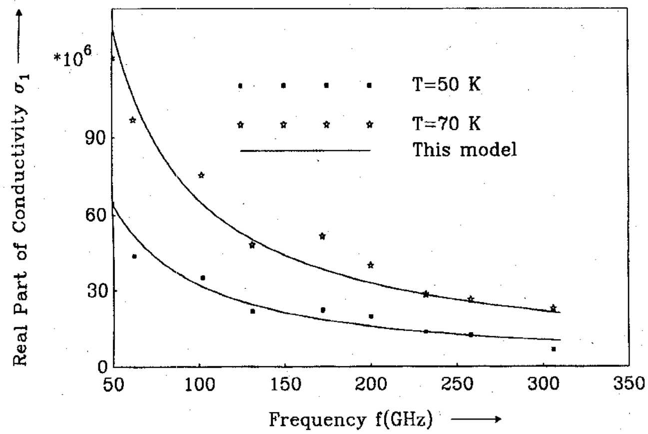

Fig. 3. The frequency dependence of the real part of the conductivity σ_1 in $1/\Omega\text{m}$ for YBCO. The experimental data are taken from [11], and $\sigma_n = 1.15 \times 10^6\ 1/\Omega\text{m}$.

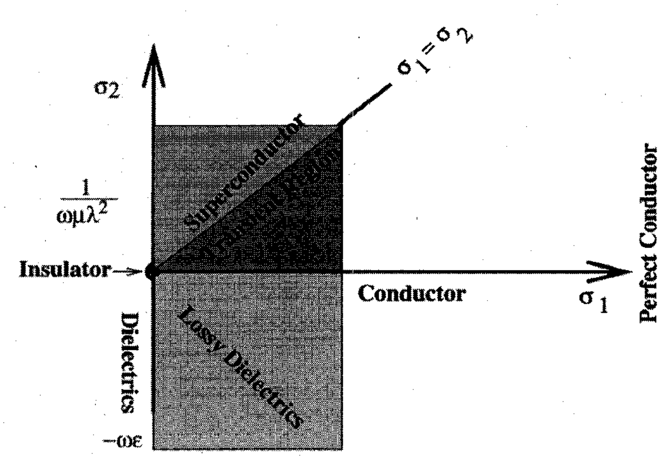

Fig. 4. Conductivity plane for dielectrics, insulators, conductors, and HTS's.

dependent on the driving frequency with the same behavior as σ_2. Nuss *et al.* in [11] have published their measured results of surface impedances R_s and X_s up to 500 GHz. Using the relation between $Z_s = R_s + jX_s$ and $\sigma = \sigma_1 - j\sigma_2$, σ_1 can be extracted from their measured values of R_s and X_s. Using well-known data-fitting techniques, (7) can be fitted to the measured data. In Fig. 3, simulated curves from our model are compared with the measured values extracted from [11]. The theoretical and measured results show good agreement, and indeed σ_1 is a function of frequency. Within the total frequency range shown in Fig. 3 σ_1 is always larger than σ_n. In this frequency range the experimental results of R_s show that the surface resistance R_s will increase as the driving frequency increases, but the related real part of the conductivity of YBCO decreases. This behavior is really the same as that of a good conductor: smaller surface resistance is related to larger σ_1 in this temperature range, but is not like the theoretical predicted behavior that smaller surface resistance is related to smaller σ_1 by the two-fluid model. From (7) it is known that $\sigma_1/\sigma_n = f(t) + (1/\alpha(T))(\sigma_2/\sigma_n)$. Because σ_2 is very much larger than σ_n in the superconducting state, it is possible that $\sigma_1 > \sigma_n$ from this model if the model parameter $\alpha(T)$ is chosen suitably. For the two-fluid model it is impossible to simulate $\sigma_1 > \sigma_n$.

B. HTS = Perfect Conductor?

For applications of HTS's the high-T_c superconductive boundary value problems of electromagnetic fields must be solved. In classical applications of superconductors, superconductive boundaries are considered as perfect conducting boundaries (see, e.g., [13] and [14]). Therefore, all results of normal conducting waveguides are directly overtaken to analyze HTS's waveguides. But actual research indicates that there are big differences between HTS's and perfect conductors as in [1] and [5].

1) In perfect conductors, electrons have **no** scattering, but in HTS's the electrons bounded in Cooper pairs have scattering even if the driving temperature is absolute zero [5, p. 529].
2) HTS's demonstrate the magnetic flux (Meißner) effect, but perfect conductors do not.
3) It is well known that the real and imaginary parts of the complex conductivity of perfect conductors are infinite and zero, respectively, but measured data show that for HTS's it is always $\sigma_2 > \sigma_1$ (see, e.g., [9] and [10] and references therein).

For an ideal dielectric material only a displacement current $\boldsymbol{J}_d = j\omega\epsilon\boldsymbol{E}$ is defined. If we consider a dielectric material as an "effective" conductor with "effective" conductivity $\sigma_d = \sigma_{1d} - j\sigma_{2d}$ and $\boldsymbol{J}_d = \sigma_d\boldsymbol{E}, \sigma_{1d} = 0, \sigma_{2d} = -\omega\epsilon$ are obtained. That is, a dielectric material can be considered as an "effective" conductor with a negative imaginary part of the "effective" conductivity. From this point of view, all materials can be drawn in the conductivity plane as shown in Fig. 4. It indicates obviously that there are big differences between HTS's and perfect conductors. Therefore, instead of using perfect conducting boundary conditions to solve high-T_c superconductive boundary value problems in electromagnetics, an alternative boundary condition must be proposed.

C. Effective Dielectric Constant

For defining the effective relative dielectric constant, $\overline{\epsilon_r}$, (7) and (8) are substituted into Ampere's law as follows:

$$\begin{aligned}\nabla \times \boldsymbol{H} &= j\omega\epsilon_o\overline{\epsilon_r}\boldsymbol{E} = j\omega\epsilon_o\epsilon_r\boldsymbol{E} + \boldsymbol{J} \\ &= j\omega\epsilon_o\left(\epsilon_r - \frac{\sigma_2}{\omega\epsilon_o} - \frac{\sigma_1}{\omega\epsilon_o}\right)\boldsymbol{E} \qquad (11)\end{aligned}$$

where $\boldsymbol{J}$ is total current density defined in (4) and $\epsilon = \epsilon_o\epsilon_r$ is the dielectric constant of the HTS. The effective dielectric constant can be obtained as

$$\begin{aligned}\overline{\epsilon_r}(\omega) = \epsilon_r &- \left(\frac{\omega_s}{\omega}\right)^2\frac{(\omega\tau_s)^2}{1+(\omega\tau_s)^2} - \left(\frac{\omega_n}{\omega}\right)^2\frac{(\omega\tau_n)^2}{1+(\omega\tau_n)^2} \\ &+ \frac{1}{j}\left[\left(\frac{\omega_s}{\omega}\right)^2\frac{\omega\tau_s}{1+(\omega\tau_s)^2} + \left(\frac{\omega_n}{\omega}\right)^2\frac{\omega\tau_n}{1+(\omega\tau_n)^2}\right] \qquad (12)\end{aligned}$$

with

$$\omega_s^2 = \frac{q^2 n_s}{m\epsilon_o}, \quad \omega_n^2 = \frac{q^2 n_n}{m\epsilon_o} \qquad (13)$$

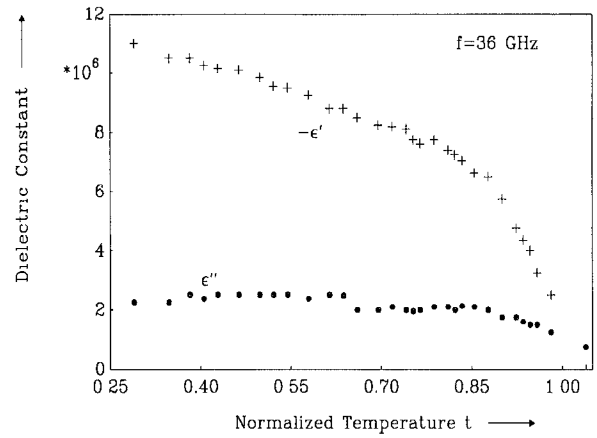

Fig. 5. Calculated effective complex dielectric constant of YBCO as a function of normalized temperature at $f = 36$ GHz. Measured data of σ_1 and σ_2 given by Bhasin *et al.* in [9] are used as basis for the calculations.

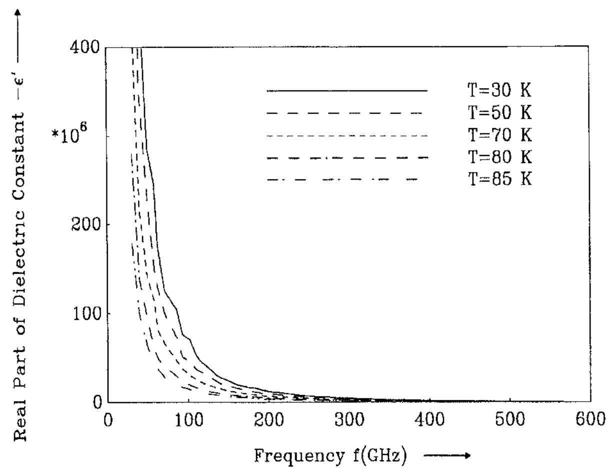

Fig. 6. Calculated real part of the complex dielectric constant of YBCO as a function of frequency for different temperatures.

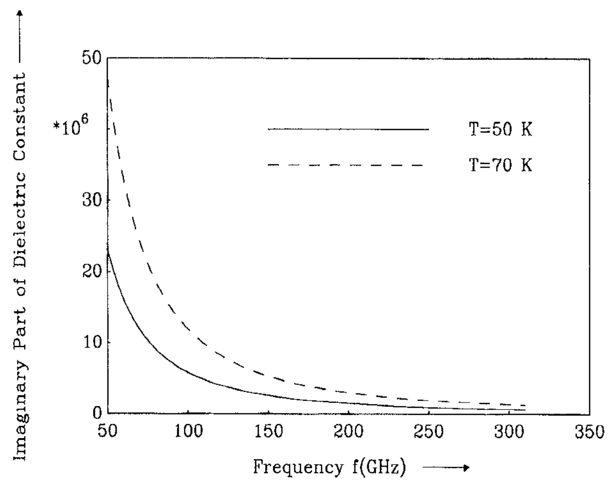

Fig. 7. Calculated imaginary part of the complex dielectric constant of YBCO as a function of frequency for different temperatures.

which are the plasma frequencies of the super- and normal-conducting particles. An alternative form of (12) in terms of the real and imaginary parts of $\overline{\epsilon_r}(\omega) = \epsilon' - j\epsilon''$ is

$$\epsilon'(\omega) = \epsilon_r - \left(\frac{\omega_s}{\omega}\right)^2 \frac{[\alpha(T)]^2}{1+[\alpha(T)]^2} - \left(\frac{\omega_n}{\omega}\right)^2 \frac{(\omega\tau_n)^2}{1+(\omega\tau_n)^2} \tag{14}$$

$$\epsilon''(\omega) = \left(\frac{\omega_s}{\omega}\right)^2 \frac{\alpha(T)}{1+[\alpha(T)]^2} + \left(\frac{\omega_n}{\omega}\right)^2 \frac{\omega\tau_n}{1+(\omega\tau_n)^2} \tag{15}$$

where (10) has been used. In Fig. 5 the complex dielectric constant of YBCO is shown as a function of the normalized temperature at $f = 36$ GHz. Here the measured values of the complex conductivity of YBCO given by Bhasin *et al.* in [9] are used as basis for the calculations. It indicates that the real part of the complex dielectric constant is negative as required by Mei *et al.* in [12], but the imaginary part of the complex dielectric constant of YBCO does not diminish as temperature decreases, which is also a conclusion of Mei *et al.* [12, Fig. 1(b), p. 1547]. The results of Mei *et al.* indicate that the magnitude of $|-\epsilon'|$ is much larger than that of $|\epsilon''|$ in order, but Fig. 5 shows that this is not true according to the measured data, and $|-\epsilon'|$ and $|\epsilon''|$ are in the same order for the sample used in [9] and applying the new developed theoretical background [1].

The frequency dependences of the real and the imaginary part of the complex dielectric constant for YBCO are shown in Figs. 6 and 7 using the measured values of the conductivity of YBCO given in [11].

D. The Meißner Effect

The experimental fact show that dc magnetic flux is displaced from the interior of a superconductor (the Meißner effect). This effect is also found in HTS's. The high-frequency properties of HTS's must be understood in order to use them practically in microwave engineering.

Microwave radiation incident upon the surface of a HTS of infinite size is supposed. For definiteness, its surface is taken to be the xy plane, and normal incidence is discussed, so that the wave propagation is in the z-direction. Finally, attention is restricted to plane-polarized radiation, and the x axis is taken along the direction of the $\boldsymbol{E}$ vector, so that $\boldsymbol{E} = (E, 0, 0)$ and $\boldsymbol{H} = (0, H, 0)$. The propagation in the HTS is governed by Maxwell's equation with Ohm's law. If $\boldsymbol{J}$ and $\boldsymbol{E}$ are eliminated, the following equation for $\boldsymbol{H}$ can be found

$$\nabla^2 \boldsymbol{H} = (j\omega\mu_o\sigma - \omega^2\mu_o\epsilon)\boldsymbol{H} \tag{16}$$

in which the first term on the right-hand side results from the sum of super- and normal-conducting current $\boldsymbol{J}$, and the second one from the displacement current. For a plane-wave $\nabla^2 = \partial^2/\partial z^2$. Then, solution of (16) is $\boldsymbol{H} = \boldsymbol{H}_o \exp(j\omega t - \gamma z)$ and

$$\gamma^2 = j\omega\mu_o\sigma - \omega^2\mu_o\epsilon = j\omega\mu_o\sigma_1 + \omega\mu_o\sigma_2 - \omega^2\mu_o\epsilon \tag{17}$$

which is an attenuated plane wave.

It is obvious that $\gamma = \alpha + j\beta$ is a complex quantity. For good conductors $\alpha = \beta = \sqrt{\pi f \mu_o \sigma_n}$ which leads to the skin effect. In microwave integrated circuits this skin-effect plays an important role and has been studied in detail, e.g., by Waldow and Wolff in [3]. But for HTS's we can derive α

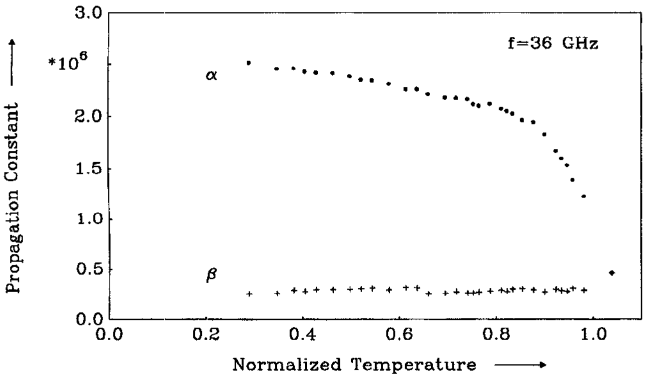

Fig. 8. Propagation constants of YBCO at $f = 36$ GHz in 1/m using the measured data in [9] in dependence on the normalized temperature $t = T/T_c$.

and β from (17)

$$\alpha = \frac{1}{\sqrt{2}}[\sqrt{(\omega\mu_o\sigma_1)^2 + (\omega\mu_o\sigma_2 - \omega^2\mu_o\epsilon)^2} + (\omega\mu_o\sigma_2 - \omega^2\mu_o\epsilon)^2]^{1/2} \approx \frac{1}{\lambda}, \quad (18)$$

$$\beta = \frac{1}{\sqrt{2}}[\sqrt{(\omega\mu_o\sigma_1)^2 + (\omega\mu_o\sigma_2 - \omega^2\mu_o\epsilon)^2} - (\omega\mu_o\sigma_2 - \omega^2\mu_o\epsilon)^2]^{1/2} \approx \frac{1}{2}\frac{\sigma_1}{\sigma_2} \quad (19)$$

where $\omega\mu_o\sigma_2 = 1/\lambda^2 \gg \omega^2\mu_o\epsilon$ and $(\sigma_1/\sigma_2)^2 \ll 1$ have been used.

Equation (18) indicates that the magnetic field can exist only within the depth $z_o = \lambda$ which is independent of the driving frequency and the same as in the dc case. It is just the Meißner effect. That is, the Meißner effect is valid also in the microwave frequency range. Now the phase propagation constant β is very small.

In Fig. 8 the attenuation constant α and the phase constant β of YBCO are shown at $f = 36$ GHz. Again the measured complex conductivity given by Bhasin *et al.* in [9] is used for the calculations. The penetration depth is $z_o = 1/\alpha$ which is less than 0.5 μm. For perfect conductors the dc case is largely different from the ac case, in the dc case the magnetic field can penetrate the sample, but in the ac case the penetration depth is zero. For HTS's both the dc and the ac cases are equal.

III. Nonlinear Microwave Surface Resistance

The surface resistance R_s of any superconductor will clearly become nonlinear with respect to the applied magnetic field near the critical magnetic field strength H_c [15]–[17], because the applied magnetic field modifies the superconducting and normal electron densities [16]. The nonlinearity of the surface resistance limits the power-handling capability of a given microwave structure. For this reason, it is desired that a suitable model can be used to model and simulate this nonlinear effect. But the surface resistance R_s with applied magnetic field has not yet been modeled or simulated accurately as mentioned in [15] and [16].

In order to simulate the magnetic field dependence of the surface resistance $R_s(H)$ for YBCO, Nguyen *et al.* in [15] and [17] assumed that

$$R_s(T, \omega, H) = R_s(T, \omega, 0)[1 + b_R(T, \omega)H^2] \quad (20)$$

where the introduced model parameter b_R is determined using a least-squares fitting to the measured data. But in high-field regime the simulated results using (20) do not agree with the experimental results presented by the same authors, as written in [15]: "if H is large, R_s increases faster than H^2." In this section, we will use the new model to simulate the surface resistance under the influence of an applied magnetic field.

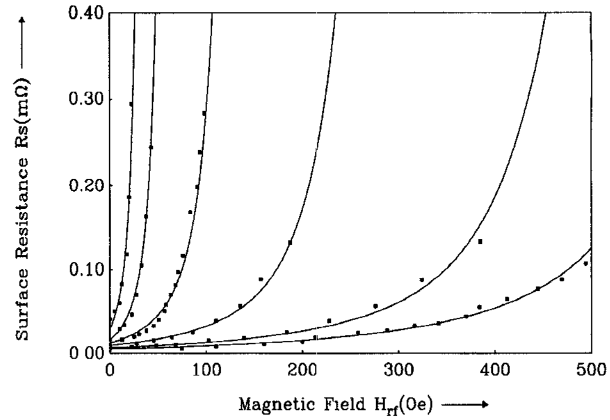

Fig. 9. R_s vs H at $f = 1.5$ GHz for different temperatures $T = 4.3$ K, 46.9 K, 65.6 K, 77.4 K, and 84.3 K from right to left. • • • •: Measured data from (15). ——: Simulated results from our model.

In the new model [1], briefly mentioned in Section II, a magnetic field dependence is not explicitly included. However, because the applied magnetic field can affect the penetration depth of HTS's, we can assume that the applied field has an effect only on model parameter α as given in (10)

$$\alpha(T, H) = \alpha(T)e^{-M_R(T)H} \quad (21)$$

where $M_R(T) > 0$ (in order to ensure that $H \rightarrow H_c$ and $\lambda \rightarrow \infty$) is a model parameter which can be derived from measured values. Substituting (21) into the expression for R_s derived in [1], the nonlinear surface resistance in dependence of the applied magnetic field can be obtained. M_R can be determined using data fitting techniques, e.g., as that used in [15]. Now $R_s(T, H)$ versus H at a given temperature can be simulated. In Figs. 9 and 10 our simulated results are compared with measured curves given by Nguyen *et al.* in [15] and [17]. They show a very good agreement.

IV. Conclusion

The paper presents an understanding of high-temperature superconductors in the context of classical electrodynamics using a new proposed model of HTS's. The basics of electromagnetic properties in HTS's are discussed and some electrical properties are modeled and simulated. The differences between "perfect conductor" and "high-T_c superconductors" are presented. For the first time the frequency dependence of the real part of the conductivity for HTS's is accurately predicted and simulated using a theoretical model. The discussions presented in this paper will be helpful to microwave engineers involved with the applications of HTS's. The good agreement between

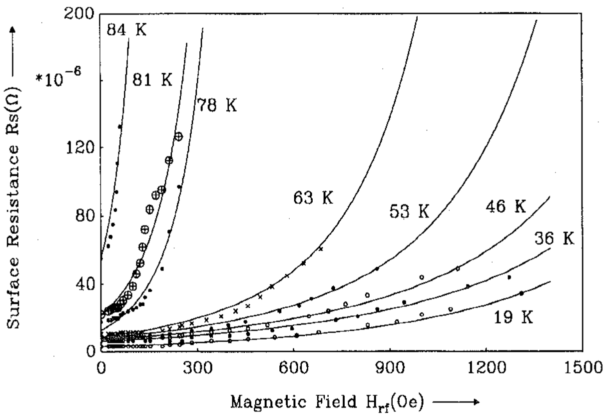

Fig. 10. R_s vs H at $f = 1.5$ GHz for different temperatures. ——: Simulated curves from our model. Symbols are measured data from [17].

simulated results from the new model and measured results from the literature demonstrates that this model should be applicable to microwave design purposes.

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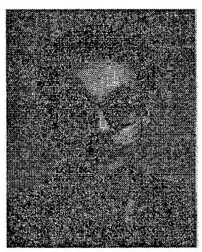

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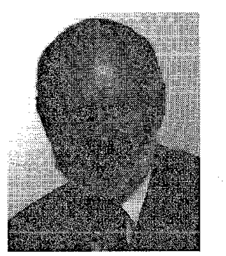

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