Modeling the Microwave Properties of Superconductors

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***Abstract*—In this paper a macroscopic phenomenological model for the microwave properties of superconductors is presented. The model is based on the idea that there are two kinds of current carriers, and instead of the first London's equation a new equation is derived. This model can be applied to both low- and high-temperature superconductors. Using this model, an expression for the microwave surface resistance is derived and the surface resistance versus frequency is calculated. The results show that the relation between resistance and frequency is not $R_s \sim \omega^2$ as indicated by both BCS theory and London model, but $R_s \sim \omega^a$, where a is between 1 and 2 (e.g. $a = 1.35$) for thin film high-T_c superconductors $YBa_2Cu_3O_{7-\delta}$. The temperature dependence of R_s is simulated using the given model. These relations and the values of the surface resistance agree well with experimental results. A residual resistance may be interpreted from this model.**

I. Introduction

HIGH-FREQUENCY superconducting components can be used for many applications. Since the surface resistance plays an important role in designing microwave components, it is very essential to determine it and its frequency dependence for the superconducting materials, especially for the high-T_c superconductors as has been demostrated, both in experimental [1]–[16] and theoretical investigations [17]–[20]. But the theoretical results [11]–[16] unfortunately do not always agree with the experimental ones, and the measured R_s is not always proportional to ω^2 as indicated by the most of the available theories [14]–[16]. So for example, in [16] measurements of the surface resistance R_s of high T_c YBCO material in the frequency range from 1–10 GHz have been presented and the result for the frequency dependence of R_s is that it varies with frequency as f^a, where a is between 1.1 and 1.4. Also the authors report that the measured R_s value is much higher than that predicted by conventional BCS theory [11], [13], [29]. In [15] the surface resistance R_s is found to have a frequency dependence f^a with $a = 1.4 \pm 0.1$ in a frequency range from 1–20 GHz. Reference [31] shows that the frequency dependence of the surface resistance varies with $f^{1.5}$ at low temperature. Similar results are described by Alford *et al.* [30] whose conclusion is $1 < a \leq 2$ and "R_s in bulk materials is not *a priori* a squared function of frequency. In this study it is observed that the frequency dependence of the extruded wires is between $f^{1.2}$ and $f^{1.4}$. None of the wires exhibits a frequency squared dependence. Early work by Grebenkemper *et al.* [37] showed that R_s of conventional metallic superconductors such as tin varied as $f^{1.5}$." The other measured results of R_s show also $1.1 \leq a \leq 1.3$ [35] and $1.3 \leq a \leq 1.7$ [36], respectively.

To effectively use superconductors in engineering applications, a better description of the superconducting mechanism in terms of its microwave parameters is required. Without a tractable model of the phenomena, it is difficult to design a practical system. Although BCS theory [11], [13], [29] and London Two-Fluid Model [11], [13], [25] are models generally accepted as microscopic- and macroscopic theories for conventional superconductors, they have limitations, as mentioned above, and they are not always able to explain the phenomena of high-T_c superconductors in the microwave range correctly [13], [29]. Now "There is no theory which conclusively explains the observed frequency dependence of the surface resistance" [35].

Since there is no generally accepted microscopic theory of high-T_c superconducting materials [28], the objective of this paper is to derive a macroscopic model of superconductivity based on the idea that there are two kinds of currents in the superconductor just like in the Two-Fluid Model. However, instead of the first London's equation an equation that considers the effect of an alternating high frequency field will be derived. The neglectance of this effect possibly is the reason for the discrepancies between theory and experiments for the residual resistance reported in the literature [6], [11]. Without going into a physical discussion, it is assumed in this paper that additional losses occur inside the superconducting material, which will be considered in the theoretical model without further justification. Using this model, a relation of the surface resistance versus frequency for high-T_c thin-film superconductors, as they are normally used in microwave applications, is presented and the values of the actual resistances of YBCO and Nb are calculated. These results agree well with published experimental results. It should be pointed out that the presented model can only be valid for thin films because results extracted from thin film measurements are used for its derivation. But nevertheless, this model should also be applicable to other materials.

II. Basic Equations

It is assumed that in a superconductor there are two kinds of current carriers, superparticles, and normal electrons (quasi-particles) with n_s and n_n being their particle densities, respectively. The sum of these two carrier densities is the total

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density

$$n = n_s + n_n \tag{1}$$

and the temperature dependences of both carrier densities satisfy

$$\frac{n_s}{n} = 1 - f(t), \quad \frac{n_n}{n} = f(t), \quad \text{and} \quad t = \frac{T}{T_c}. \tag{2}$$

Here, T_c is the critical temperature of the superconductor and $f(t)$ is a function of normalized temperature t. Using fitting data there are many functional expressions for the temperature dependence of high temperature superconductors presented in the literature. For examples, Gorter-Casimir [5] expression

$$f(t) = t^4, \tag{3}$$

an empirical expression proposed by Rauch *et al.* [45]

$$f(t) = 0.1t + 0.9t^2, \tag{4}$$

a Boltzmann-type expression given by G. F. Dionne [46]

$$f(t) = e^{W - W/t}, \tag{5}$$

where W is a model parameter, an approximation to BCS theory assumed by Bonn *et al.* [47]

$$f(t) = t^{3-t}, \tag{6}$$

the expression used by Pakulis *et al.* [33]

$$f(t) = t, \tag{7}$$

or the bipolaron model repeatedly discussed by Vendik *et al.* [48]

$$f(t) = t^{3/2}. \tag{8}$$

Under the influence of an external electric field, as mentioned above, both particles obey Newton's law of motion as follows:

$$m\frac{d\vec{v}_s}{dt} = q\vec{E} \tag{9}$$

$$m\frac{d\vec{v}_n}{dt} + m\frac{\vec{v}_n}{\tau_n} = q\vec{E}, \tag{10}$$

where $\vec{v}_s$ is the velocity of the superparticles, $\vec{v}_n$ is the average velocity of the normal electrons, which have a momentum relaxation time τ_n, and m and q are the mass and charge of a single particle, respectively. The superparticle is treated as a collisionless particle, while the scattering process of the normal electrons is approximately represented by the parameter τ_n. That is, we assume the particles and the electric field to obey a local relation and the field to be extremely low, so that the nonlinearity of the superconductor can be neglected in this first step of approximation.

Let $\vec{J}_s$ and $\vec{J}_n$ be the super- and normal-current densities. The total current density then is the sum of the two parts. Thus

$$\vec{J}_s = n_s q \vec{v}_s, \tag{11}$$

$$\vec{J}_n = n_n q \vec{v}_n, \tag{12}$$

with

$$\vec{J} = \vec{J}_s + \vec{J}_n. \tag{13}$$

Assuming that the normal electrons have no net charge accumulation with varying external fields, that is

$$\frac{\partial n_n}{\partial t} = 0$$

then from (10) we have

$$\frac{d\vec{J}_n}{dt} + \frac{1}{\tau_n}\vec{J}_n = \frac{q^2 n_n}{m}\vec{E}. \tag{14}$$

A study of the literature [30] shows that high-T_c superconductors apparently suffer from some loss mechanisms that cannot easily be described by the physics of superconductors. Furthermore Mei *et al.* [22] have shown that required causality conditions imposed to superconducting materials "indicate that the superfluid cannot be truly lossless to an ac field." To describe the high frequency material parameters in a better agreement with measurements and to meet the causality requirement, we postulate that the superparticle density n_s due to the losses (e.g. imperfections) has a small variation in dependence on the time with varying external electromagnetic fields. Here, we will not go into a physical discussion of this postulate. Differentiating (11) we get

$$\frac{d\vec{J}_s}{dt} = qn_s\frac{d\vec{v}_s}{dt} + q\vec{v}_s\frac{dn_s}{dt}. \tag{15}$$

We derive from (9) and (11)

$$\frac{d\vec{v}_s}{dt} = \frac{q}{m}\vec{E}, \quad q\vec{v}_s = \frac{\vec{J}_s}{n_s}.$$

Substituting these results into (15)

$$\frac{d\vec{J}_s}{dt} - \frac{1}{n_s}\frac{dn_s}{dt}\vec{J}_s = \frac{q^2 n_s}{m}\vec{E} \tag{16}$$

or

$$\frac{d\vec{J}_s}{dt} + \frac{1}{\tau_s}\vec{J}_s = \frac{q^2 n_s}{m}\vec{E}, \tag{17}$$

where τ_s is a phenomenological parameter that shall describe the recognized losses (e.g. intergranular losses [33]) in ceramic thin film superconductors. The parameter τ_s additionally may be a function of the frequency and the temperature. If the external alternating field is static ($f = 0$) or the temperature T is zero, τ_s must be infinite. Under this condition (17) becomes the first London equation [25].

Equation (17) is our basic equation instead of the first London's equation. Using it with Maxwell's equations, the question of how to describe superconductors at micro- and millimeter wave frequencies can be treated.

III. The Surface Resistance

According to the model given above, if the external field is

$$\vec{E}(\vec{r}, t) = \text{Re}\{\vec{E}(\vec{r})e^{j\omega t}\}$$

(14) and (17) become

$$j\omega\vec{J}_n + \frac{1}{\tau_n}\vec{J}_n = \frac{n_n q^2}{m}\vec{E}, \tag{18}$$

$$j\omega\vec{J}_s + \frac{1}{\tau_s}\vec{J}_s = \frac{n_s q^2}{m}\vec{E}. \tag{19}$$

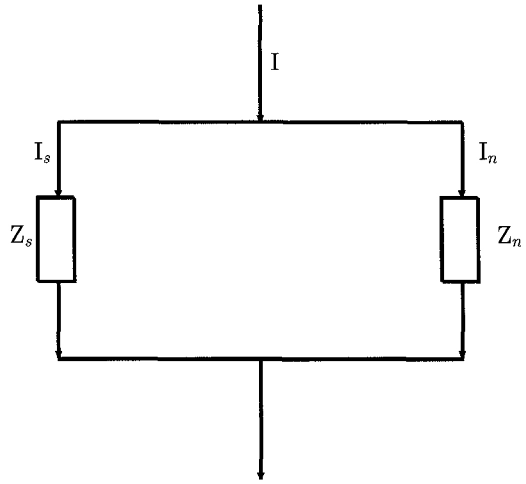

Fig. 1. Equivalent circuit for superconducting material at high frequencies.

Where the field values now are complex variables without special notations. The current densities can be represented schematically by the currents I_n and I_s in the circuit shown in Fig. 1. Both the normal electron current I_n and the superconducting current I_s are in parallel shunted since the current densities see the same electric field. Here Z_s and Z_n are impedances representing the "superparticle channel" and the "normal particle channel" similar to the circuit in [5], respectively: $Z_s = j\omega L_s + R_s$ and $Z_n = j\omega L_n + R_n$. L_s, R_s and L_n, R_n are interpreted as the "inductances" and "resistances" of the two channels, respectively.

Using Ohm's law and a complex conductivity $\sigma = \sigma_1 - j\sigma_2$

$$\vec{J} = \vec{J}_s + \vec{J}_n = \sigma\vec{E} = (\sigma_1 - j\sigma_2)\vec{E} \tag{20}$$

and substituting (18) and (19) into (20), we have

$$\sigma_1 = \frac{n_n q^2}{m\omega}\frac{\omega\tau_n}{1+(\omega\tau_n)^2} + \frac{n_s q^2}{m\omega}\frac{\omega\tau_s}{1+(\omega\tau_s)^2}, \tag{21}$$

$$\sigma_2 = \frac{n_n q^2}{m\omega}\frac{(\omega\tau_n)^2}{1+(\omega\tau_n)^2} + \frac{n_s q^2}{m\omega}\frac{(\omega\tau_s)^2}{1+(\omega\tau_s)^2}. \tag{22}$$

Treating a superconductor like a good ohmic conductor, the expression for the surface impedance is still valid [11]–[13] and can be determined from its conductivity

$$Z_s = \sqrt{\frac{j\omega\mu_0}{\sigma}} = \sqrt{\frac{j\omega\mu_0}{\sigma_1 - j\sigma_2}}. \tag{23}$$

From (23) the microwave surface resistance of a superconductor R_s is now given by [6]

$$R_s = \sqrt{\frac{\omega\mu_0}{2}}\left[\frac{\sqrt{\sigma_1^2+\sigma_2^2} - \sigma_2}{\sigma_1^2+\sigma_2^2}\right]^{\frac{1}{2}}. \tag{24}$$

If $\tau_s \to \infty$, (21) and (22) become

$$\sigma_1 = \frac{n_n q^2}{m\omega}\frac{\omega\tau_n}{1+(\omega\tau_n)^2}, \tag{25}$$

$$\sigma_2 = \frac{n_n q^2}{m\omega}\frac{(\omega\tau_n)^2}{1+(\omega\tau_n)^2} + \frac{n_s q^2}{m\omega}, \tag{26}$$

and (24) becomes

$$R_s = 0.5\sqrt{\frac{\omega\mu_0}{\sigma_2}}\frac{\sigma_1}{\sigma_2}. \tag{27}$$

Now (25)–(27) are identical to the equations given in [11]–[13].

Using the same assumptions as those in [11]–[13] in the microwave range and

$$\frac{n_n q^2}{m\omega}\frac{(\omega\tau_n)^2}{1+(\omega\tau_n)^2} \ll \frac{n_s q^2}{m\omega}\frac{(\omega\tau_s)^2}{1+(\omega\tau_s)^2},$$

R_s can be approximately written as

$$R_s \approx 0.5\mu_0^2\lambda^3\sigma_n f(t)\omega^2 + 0.5\frac{\mu_0\lambda\omega}{(\omega\tau_s)}, \tag{28}$$

where σ_n is the conductivity at room-temperature and [13]

$$\sigma_2 \approx \frac{1}{\omega\mu_0\lambda^2}. \tag{29}$$

Now

$$\lambda^2 = \frac{m}{n_s q^2\mu_0}\left[1 + \frac{1}{(\omega\tau_s)^2}\right] = \lambda_L^2\left[1 + \frac{1}{(\omega\tau_s)^2}\right] \tag{30}$$

and

$$\lambda_L = \sqrt{\frac{m}{n_s q^2\mu_0}} \tag{31}$$

is the London penetration depth, which is also a function of the temperature

$$\frac{\lambda_L(T)}{\lambda_0} = [1 - f(t)]^{-\frac{1}{2}}, \quad \lambda_0 = \lambda_L(0). \tag{32}$$

Using these relations, (28) can be rewritten

$$R_s \approx 0.5\mu_0^2\lambda_0^3\sigma_n\frac{f(t)(1+\frac{1}{(\omega\tau_s)^2})^{\frac{3}{2}}}{[1-f(t)]^{\frac{3}{2}}}\omega^2 + 0.5\frac{\mu_0\lambda_0}{\omega\tau_s}\frac{\sqrt{1+\frac{1}{(\omega\tau_s)^2}}}{\sqrt{1-f(t)}}\omega. \tag{33}$$

It is generally assumed that the parameter λ is independent of the frequency and is only a function of temperature T [13]. Therefore, it is required that the term $\omega\tau_s$ must be not a function of frequency. This leads to

$$\omega\tau_s = \alpha, \quad \text{or} \quad \tau_s = \frac{\alpha}{\omega}. \tag{34}$$

Here α no longer varies with frequency but may still be a function of the temperature T. Substituting this into (33)

$$R_s \approx 0.5\mu_0^2\lambda_0^3\sigma_n\frac{f(t)(1+\frac{1}{\alpha^2(t)})^{\frac{3}{2}}}{[1-f(t)]^{\frac{3}{2}}}\omega^2 + 0.5\frac{\mu_0\lambda_0}{\alpha(t)}\frac{\sqrt{1+\frac{1}{\alpha^2(t)}}}{\sqrt{1-f(t)}}\omega. \tag{35}$$

In (28) or (33) the first term is the same as the surface resistance resulting from the London Two-Fluid Model, which is proportional to ω^2. The last term is added from this model and it is proportional to ω. It indicates that the surface resistance R_s is a function of both temperature and frequency. The temperature dependence is described using the expression $f(t)$ given in (2). This expression is different from those given by other research groups. From the discussion given above it is obvious that the equivalent London penetration depth λ has a temperature dependence

$$\lambda = \lambda_0 \sqrt{1 + \left[\frac{1}{\alpha(t)}\right]^2} \Big/ \sqrt{1 - f(t)} \tag{36}$$

which is different from that given by the conventional Two-Fluid Model. The temperature dependence $f(t)$ of the current carriers, defined in (2), is one of the defined functions given above in (3)–(8). The temperature dependence of the penetration depth λ_L as defined in (32) is described using only the function $f(t)$. In our model an additional temperature function $\alpha(t)$ is added as shown in (36), which can be considered as an unkown model parameter. This parameter $\alpha(t)$ can be extracted from experimentally measured surface resistances R_s for constant ω using any data fitting technique. Obviously, for a given set of measurement results, $\alpha(t)$ is dependent on the assumed temperature dependence $f(t)$. Once $f(t)$ is defined, $\alpha(t)$ is a function fixed by the experimentally determined data. As has already been mentioned above, only experimental results from high-T_c thin film superconductors measurements are used in this investigation, therefore the drawn results are only valid for these cases at this time.

IV. Applications

As an example the high-temperature superconductor $Y\,Ba_2Cu_3O_{7-\delta}$ [27] is discussed. Its conductivity at room-temperature is $\sigma_n = 3.9 \times 10^5\ \Omega^{-1}\mathrm{m}^{-1}$, $T_c = 86.3$ K. At frequency $f = 36$ GHz and temperature $T = 76$ K, the penetration depth is $\lambda = 0.57\ \mu$m. The conductivities obtained from experiments [27] are

$$\sigma_1 = 4.6 \times 10^6\,\Omega^{-1}\mathrm{m}^{-1}, \quad \sigma_2 = 1.3 \times 10^7\,\Omega^{-1}\mathrm{m}^{-1}.$$

From the classical Two-Fluid Model, $\sigma_1 = 3.9 \times 10^5(\frac{76}{86.3})^4\ \Omega^{-1}\mathrm{m}^{-1} = 2.3 \times 10^5\ \Omega^{-1}\mathrm{m}^{-1}$, which is much less than that obtained from experiment. That is, the additive effect of the frequency dependence (last term of (33)) must be considered. From the values of σ_1 and σ_2 determined by experiment, we have (compare (21) and (22)) $\alpha = \omega\tau_s = 3$. If we e.g. use the temperature dependence of Gorter-Casimir, R_s now is

$$\frac{R_s}{\Omega\mathrm{m}} = 0.00225\frac{(T/T_c)^4}{[\sqrt{1-(T/T_c)^4}]^3}\frac{f^2}{(\mathrm{GHz})^2} + 0.75\frac{1}{\sqrt{1-(T/T_c)^4}}\frac{f}{(\mathrm{GHz})}. \tag{37}$$

Equation (37) gives the relationship between R_s, the frequency f, and the temperature T. Equation (37) can be simulated in the form $R_s \sim \omega^a$ in the frequency range 1 GHz $\leq f \leq$ 250 GHz with $a = 1.35$. Experimental results show that $1.1 < a < 1.4$ [16] or $a = 1.4 \pm 0.1$ [15] in many nonideal thin film high-T_c superconducting materials.

From (35) it is known that a is between 1 and 2 if R_s is assumed as $R_s \sim \omega^a$. In different frequency ranges or/and

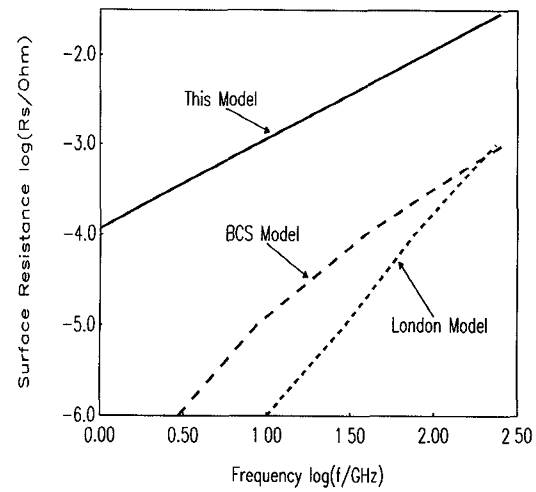

Fig. 2. The surface resistance of Nb at 4.2 K versus frequency; $T_c = 9.2$ K.

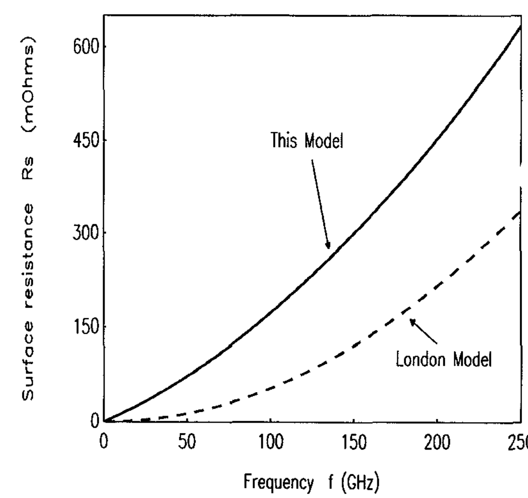

Fig. 3. The surface resistance of YBCO at 76 K versus frequency; $T_c = 86.3$ K.

in different temperature ranges the factor a may be different, e.g. in the very high frequency range, or if the temperature T is near T_c, the first term in (35) plays an important role. Under these conditions a is near to 2. At low frequencies f or for low temperatures T, it is $1.1 < a < 1.5$. These results are in agreement with those obtained from experiments [15], [16], [26]–[34].

In Fig. 2 and Fig. 3, the dependences of the surface resistances versus frequency for low- and high-temperature superconductors are given. The results of London's model and the BCS model are obtained from [12], and the parameters of Nb and YBCO are taken from [12] and [27], respectively.

As has already been mentioned, the parameter α in the model must be a function of temperature. Fig. 4(a) shows the frequency dependence of the surface resistance of YBCO at temperatures $T = 5$, 44, and 77 K, and at $T = 50$, 70, 80, and 85 K in Fig. 4(b). The experimental data are taken from [38] at $T = 5$ and 44 K, and [16] at $T = 77$ K. The experimental data in Fig. 4(b) are taken from [39]. The parameter α is determined using a curve fitting to the experimental data to be (from Fig. 4(a)): $\alpha = 0.1563, \alpha = 8.23$, and $\alpha = 20.8$ for

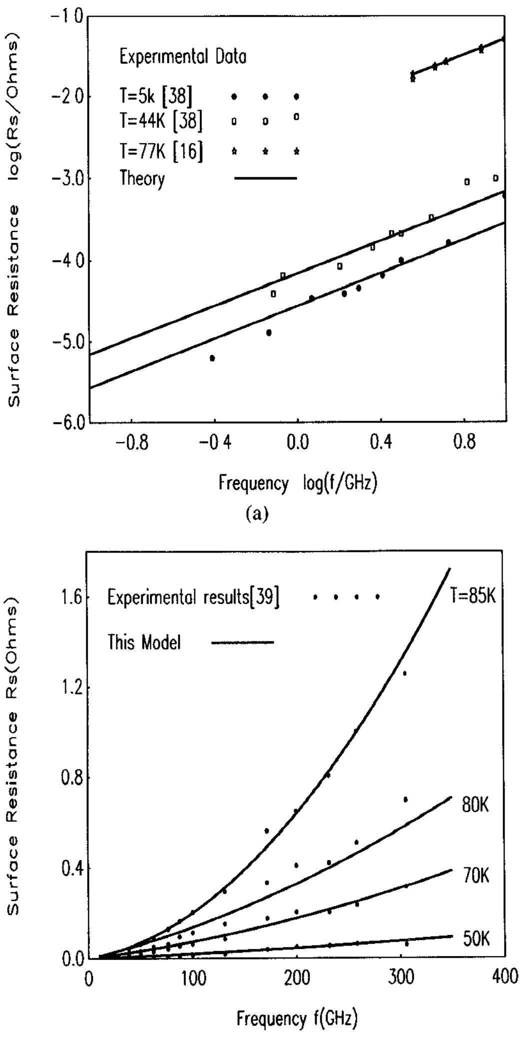

Fig. 4. Frequency dependence of the surface resistance of YBCO at different temperature.

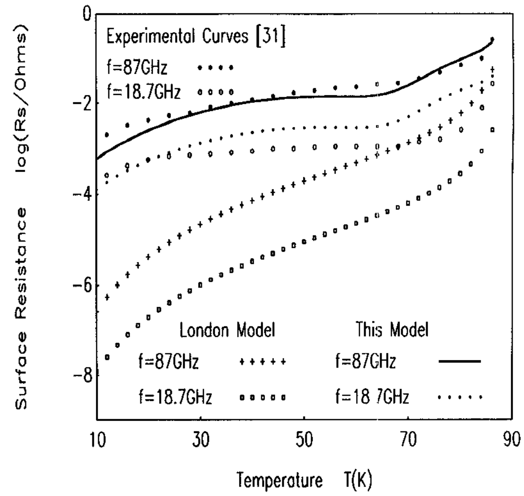

Fig. 5. Surface resitance R_s versus temperature T at f = 87 and 18.7 GHz.

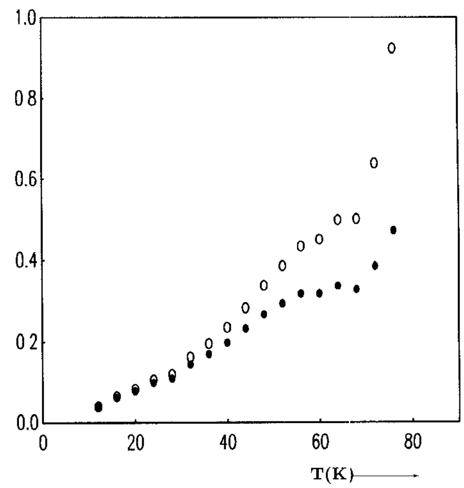

Fig. 6. Model parameter α versus temperature T. f = 87 GHz, the surface resistance given by expriment taken from [31]. Open points: $f(t) = t^4$; filled points: $f(t) = t^{1.5}$ [48].

the temperatures T = 77, 44, and 5 K, respectively. From the data given in Fig. 4(b) we get $\alpha = 5., \alpha = 3., z\alpha = 4.5$, and $\alpha = 12.51$ at temperatures T = 85, 80, 70, and 50 K, respectively. This indicates that if $T \to 0$, $\alpha(T)$ increases.

From Fig. 4 it may be recognized that the parameter α is a function of the temperature T. For a given material, an assumed temperature dependence $f(t)$ and fixed test conditions, α can be determined. Using the determined α from one of the experiments under these conditions, other experiments can be simulated using the same parameter for a given material and given test conditions. In Fig. 5 the surface resistances R_s are drawn versus temperature T for different frequencies. Here the parameter $\alpha(t)$ is the same for both frequencies.

For a given temperature dependence $f(t)$ as defined in (2), the parameter α always has an adjoint fixed temperature dependence. In the above-discussed simulations of R_s, the Gorter-Casimir expression is used. For other temperature dependences $f(t)$, the functional form of $\alpha(t)$ is determined from the experimental results by data fitting and (35). In Fig. 6 as an example the values of $\alpha(t)$ are shown for two different temperature dependences $f(t)$: Gorter-Casimir expression $f(t) = t^4$ and bipolaron expression discussed by Vendik *et al.* [48], $f(t) = t^{1.5}$. Here the driving frequency is 87 GHz and the experimental values of R_s are taken from the literature [31].

Using alternatively the two temperature expressions of $f(t)$ and the correlated values of $\alpha(t)$, the surface resistance R_s given by experiment [31] in any case can be simulated very well.

Several groups [40]–[43] have recently observed peaks in the conductivity of high-T_c superconductors at microwave frequencies near T_c. These peaks look rather different from the weak-coupling BCS coherence peaks, in the sense that they occur very close to T_c, are very narrow [44], and "It is an established experimental fact that the high-T_c cuprate superconductors show no peak below T_c for $1/T_1T$" London's model and other modified Two-Fluid Models exhibit no peak for $T < T_c$ [40], [49]. Kobayashi *et al.* [49] introduced an adjustable model factor in their three-fluid model to simulate the peaks in the conductivity of the high-T_c superconductors.

Using the model given above, the peaks can appear for $T < T_c$ if $\alpha(t)$ obeys a Gaussian distribution in dependence

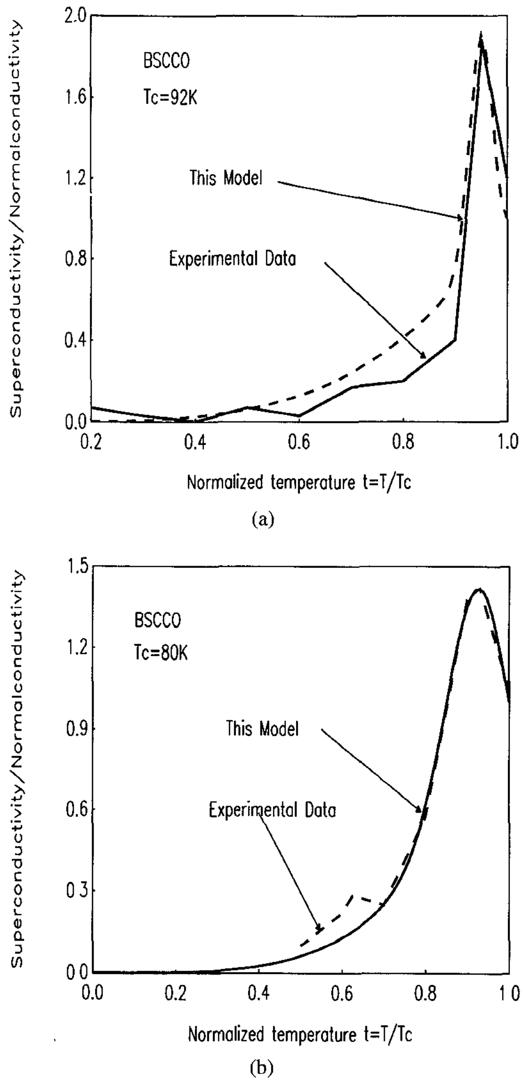

Fig. 7. Peak in the real part of the conductivity.

on the temperature T in the region near T_c. Fig. 7 shows the experimental curve obtained from [41] and the simulated curve from our theory using parameters as in [41], and the described temperature dependence of $\alpha(t)$. The agreement between the experimental results and the theoretical prediction is good for both temperatures and demonstrates well the broad applicability of the derived model.

V. Conclusion

This paper presents a macroscopic phenomenological model that correctly predicts the values of the microwave surface resistance R_s of high-T_c thin film superconductors and the relation between R_s and the frequency ω in agreement with many experiments at different temperatures. It means that the residual resistance can be described by this model. Additionally, this model can also simulate the peaks in the real part of the conductivity of a superconductor obtained from measurements near the critical temperature T_c. It is assumed, that the introduced parameter $\alpha(T)$ can be considered as a material parameter for various superconductors at micro- and millimeter-wave frequencies.

It has been demonstrated that this model is valid for both low- and high-temperature superconductors at rf and microwave frequencies. Also it is believed that the discussion presented in this paper will be helpful to microwave engineers involved in the applications of superconducting components and circuits.

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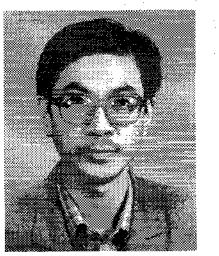

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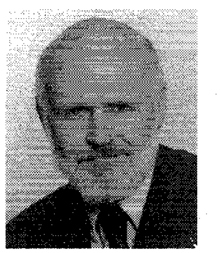

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