

HIGH TEMPERATURE SUPERCONDUCTORS APPLICATIONS IN TELECOMMUNICATIONS*

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ABSTRACT

The purpose of this paper is twofold: (i) to discuss high temperature superconductors with specific reference to their employment in telecommunications applications; and (ii) to discuss a few of the limitations of the normally employed two-fluid model. While the debate on the actual usage of high temperature superconductors in the design of electronic and telecommunications devices - obvious advantages versus practical difficulties - needs to be settled in the near future, it is of great interest to investigate the parameters and the assumptions that will be employed in such designs. This paper deals with the issue of providing the microwave design engineer with performance data for such superconducting waveguides. The values of conductivity and surface resistance, which are the primary determining factors of a waveguide performance, are computed based on the two-fluid model. A comparison between two models - a theoretical one in terms of microscopic parameters (termed Model A) and an experimental fit in terms of macroscopic parameters (termed Model B) - shows the limitations and the resulting ambiguities of the two-fluid model at high frequencies and at temperatures close to the transition temperature. The validity of the two-fluid model is then discussed. Our preliminary results show that the electrical transport description in the normal and superconducting phases as they are formulated in the two-fluid model needs to be modified to incorporate the new and special features of high temperature superconductors. Parameters describing the waveguide performance - conductivity, surface resistance and attenuation constant - will be computed. Potential applications in communications networks and large scale integrated circuits will be discussed. Some of the ongoing work will be reported. In particular, a brief proposal is made to investigate the effects of electromagnetic interference and the concomitant notion of electromagnetic compatibility (EMI/EMC) of high T_c superconductors.

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INTRODUCTION

With the high temperature superconducting materials becoming increasingly available, the interest in their applications in microwave telecommunications is on the rise [1-9]. While the debate on their actual usage in the design of electronic and telecommunications devices - obvious advantages versus practical difficulties - is still active, it is of great interest to investigate the parameters that will be employed in such designs [10,11].

This paper addresses the issue of high- T_c superconducting materials for telecommunications applications. More specifically, it focuses on the design of waveguides using high- T_c superconducting materials. The performance of a waveguide is described by the parameters such as the surface resistance of the guide wall, signal attenuation and power loss, maximum carrying frequency and bandwidth, maximum transmitted power and dynamic range. Most of these parameters are determined by the properties of the material of which the waveguide is made. High- T_c superconducting materials provide good material properties for these parameters but they also provide certain bounds for the improvement of the performance of waveguides. In this paper, the parameters are investigated with existing theory for high- T_c superconducting materials. They provide us with a better comprehension of the underlying models - their usefulness and their limitations.

Because of these advantages, and with the high- T_c superconducting materials available, recent years have seen a substantial increase in the attempts to employ high temperature superconductors in microwave telecommunications applications. The high- T_c superconductors have been used in many kinds of microwave devices such as resonators, filters, delay lines, couplers, antennas, waveguides, striplines, transmission lines, detectors, mixers, switches, oscillators, digital interconnects, wires, etc.

The main objective of this paper is to discuss some relevant parameters of the high T_c superconductors from the viewpoint of design of microwave telecommunications devices. As with any new materials a careful look at the fundamental assumptions behind the models employed should precede their actual application. The emphasis of this paper and of the discussions presented is not the exploration of fundamental theories (though a few suggestions as to their modification will be made) but the employment of existing concepts and models as applied to waveguides. More specifically we study the implications to the waveguide design based on the two-fluid model. The main intention is provide the microwave engineer with performance data available (in terms of material parameters) for different waveguide configurations - rectangular and cylindrical, in particular.

BRIEF DISCUSSION OF THE TWO-FLUID MODEL

The high temperature superconducting materials are inherently different from their low-temperature counterparts in that they are copper-oxide materials, as opposed to metallic conductors. A remarkable consequence of the high transition temperatures of the copper-oxide superconductors is a marked increase in the energy gap frequency and critical current density, as well as a decrease in the cooling price. While the research efforts

continue vigorously, at present there is no acceptable microscopic or phenomenological theory explaining the high T_c phenomenon. In the absence of such a theory, the two-fluid model seems to have served a reasonable starting point in the literature.

The two-fluid model was first introduced to provide a phenomenological description of superconductivity, in analogy with that postulated for liquid helium phase transition. In this model, the total current is assumed to be made up of a combination of normal electrons and superconducting electron pair concentration. The normal electron component is assumed to satisfy the weak scattering transport limit, while the superconducting electron pair transport is assumed to be collision-free. The movement of super-conducting and the normal electrons is expressed by the following transport equations [12]:

$$m \frac{d\bar{v}_s}{dt} = -q\bar{E} \quad (1)$$

and

$$m \frac{d\langle\bar{v}_n\rangle}{dt} + m \frac{\langle\bar{v}_n\rangle}{\tau_n} = -q\bar{E}, \quad (2)$$

In the above equations, \bar{v}_s is the velocity of the electron pairs, $\langle\bar{v}_n\rangle$ is the average velocity of the normal electrons, and m and q are the mass and charge of a single electron, respectively. The total current density is given by:

$$J = J_s + J_n,$$

$$J_s = -n_s q \bar{v}_s,$$

$$J_n = -n_n q \langle\bar{v}_n\rangle,$$

$$n = n_n + n_s.$$

In Equations 3, the various quantities have the obvious connotation: n is the total electron concentration; and n_n and n_s are the concentrations of normal electrons and superconducting electrons, and J_n , J_s are the corresponding current densities, respectively. n_n and n_s are assumed to obey the following expressions:

$$n_s = n \left[1 - \left(\frac{T}{T_c} \right)^4 \right], \quad (4)$$

and

$$n_n = n \left(\frac{T}{T_c} \right)^4 \quad (5)$$

where T_c is the critical temperature of the superconducting material.

PARAMETERS OF INTEREST - SURFACE RESISTANCE AND ATTENUATION

Surface Resistance, R_s :

The surface resistance is one of the most important parameters which determine the performance of high- T_c superconducting materials in the microwave telecommunication applications. The reason for this is that the waveguide performance related parameters such as the signal attenuation α , the power loss P_L , noise and signal dispersion depend on R_s . The Q factor of a resonator also depends on R_s .

With a complex conductivity, the surface resistance of a high- T_c superconductor R_s can be written as

$$R_s = \text{Re} \sqrt{\frac{j\omega\mu_0}{\sigma}} = \text{Re} \sqrt{j\omega\mu_0 \frac{\sigma_1 + j\sigma_2}{\sigma_1^2 + \sigma_2^2}} \quad (6)$$

Attenuation, α :

The attenuation of a waveguide can be obtained once the surface resistance is given.

For a rectangular waveguide operating in the TE_{10} mode, the attenuation α is expressed by

$$\alpha = \frac{R_s}{b\eta \sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \left[1 + \frac{2b}{a} \left(\frac{f_c}{f}\right)^2 \right] \quad (7)$$

The corresponding equation for the cylindrical waveguide operating in TE_{11} mode is

$$\alpha = \frac{R_s}{a\eta \sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \left[\left(\frac{f_c}{f}\right)^2 + 0.420 \right] \quad (8)$$

where a and b are the dimensions of the rectangular waveguide in Equation 7 and a is the radius in Equation 8.

MODELS OF COMPUTATIONS

The quantities computed are:

- conductivity σ
- surface resistance R_s
- attenuation constant α

In the literature, two different models within the two-fluid approximation seem to be used. One is a **microscopic approach (Model A)** [Mei & Liang], and the other is an **experimental fit (Model B)** [Tewksbury et al.].

Model A [Mei and Liang]:

The conductivity of the superconducting material is expressed in terms of microscopic parameters [12]:

$$\sigma = \frac{n_n q^2 \tau_n}{m(1 + \omega^2 \tau_n^2)} - j \left(\frac{n_s q^2}{m\omega} + \frac{n_n q^2 \omega^2 \tau_n^2}{m\omega(1 + \omega^2 \tau_n^2)} \right), \quad (9)$$

where τ_n is the relaxation time.

Model B [Tewksbury, et al.]:

Another approach is the experimental fit to the two-fluid model is based on the experimental data [6]

The conductivity is computed in terms of the macroscopic measurable parameters from

$$\sigma = \sigma_n \left(\frac{T}{T_c} \right)^4 - j \frac{1}{\omega \mu_0 \lambda^2(T)} \quad (10)$$

where σ_n is the normal conductivity of the material. $\lambda(T)$ is the effective penetration depth and can be found from the equation 11, where $\lambda(0)$, the effective penetration depth at temperature $T = 0$, is an experimentally measurable quantity.

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1 - \left(\frac{T}{T_c} \right)^4}} \quad (11)$$

RESULTS AND DISCUSSION

From a majority of the literature surveyed by us, we found that a consistent set of parametric values does not seem to exist for any given superconductor. To obtain typical values of the various quantities of interest, the following numerical values have been chosen [7].

$T_c=70\text{K}$, $\tau_n=2.66\times 10^{-13}\text{ s}$, $\lambda(0)=10^{-7}\text{ m}$, $\sigma_n=10^5\text{ /W m}$, $n = 10^{22}/(\text{cm})^3$, $T_c=70\text{K}$
 $\tau_n=2.66\times 10^{-13}\text{ s}$, Model A: $\sigma = \sigma_{ar} - j\sigma_{ai}$ Model B: $\sigma = \sigma_{br} - j\sigma_{bi}$

σ vs. T

Figures 1 and 2 summarize the plots of the conductivity - real and imaginary parts from equation 9 versus temperature. σ_m (sigma.a22 in the figure) and σ_{in} (sigma.a1 in the figure) are the real and imaginary parts of the conductivity contributed by the normal electrons and σ_{is} (sigma.a21 in the figure), imaginary part, is the contribution from the superconducting electrons. Our calculations show that when the temperature is lower than $0.5T_c$, the major contribution to the conductivity comes from the superconducting electrons. But as the temperature increases, the part of the conductivity due to normal electrons can no longer be neglected.

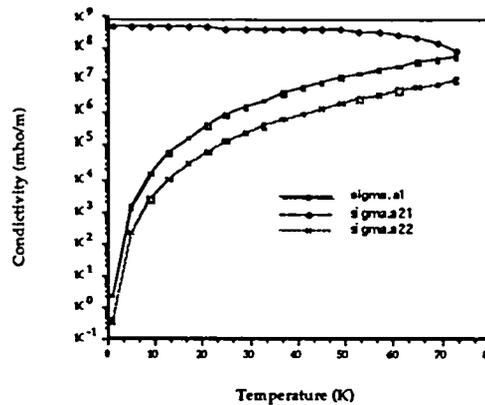


Fig. 1 Conductivity of the superconducting materials $\sigma = \sigma_m - j(\sigma_{is} + \sigma_{in})$

As can be seen, the assumption made, viz., $n_n \ll n_s$, is not valid beyond $T = 0.6 T_c$. Figure 2 summarizes the plots of the conductivity versus temperature from the two approaches.

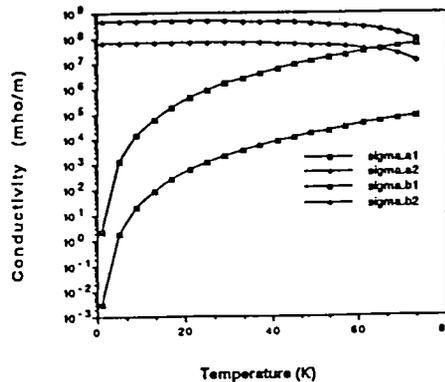


Fig. 2 Comparison of the conductivity obtained from Model A and Model B

R_s vs. frequency

Figure 3 shows the variation of R_s with the frequency. The surface resistance, while seemingly constant at low temperatures, does increase at higher temperatures.

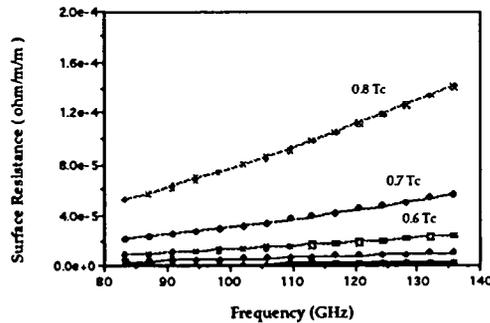


Fig. 3 Surface Resistance R_s of the High-T_c Superconducting Material at Temperatures Ranging from 0.4 T_c to 0.8 T_c

α vs. frequency

Figure 4 shows the attenuation in a superconducting waveguide. The parameters chosen for the rectangular waveguide operating in TE₁₀ mode is a=2b=2mm, f_c=75GHz, and for the cylindrical waveguide operating in the TE₁₁ mode, a=1.172mm, f_c=75GHz.

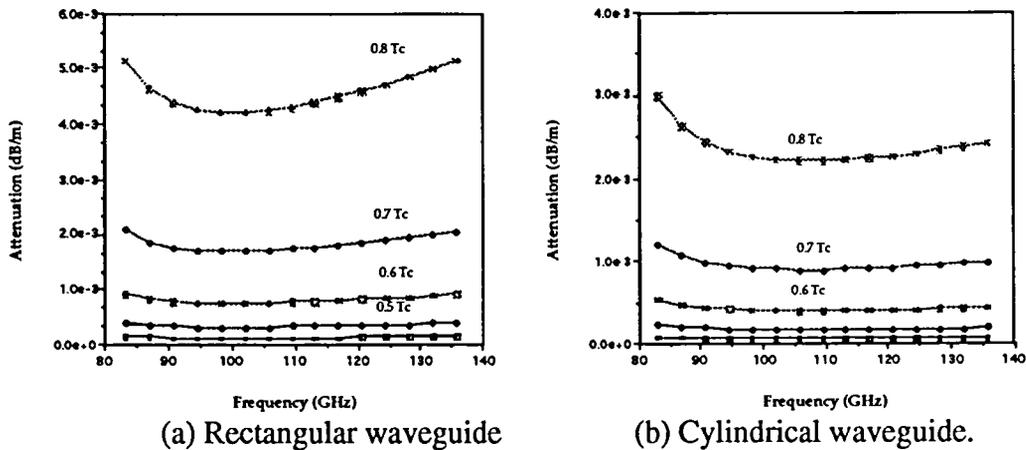


Fig. 4 The attenuation of the superconducting waveguides

Figure 5 shows the difference of the attenuation of rectangular and cylindrical waveguide modes from superconducting (at temperature 0.8 T_c) and normal material.

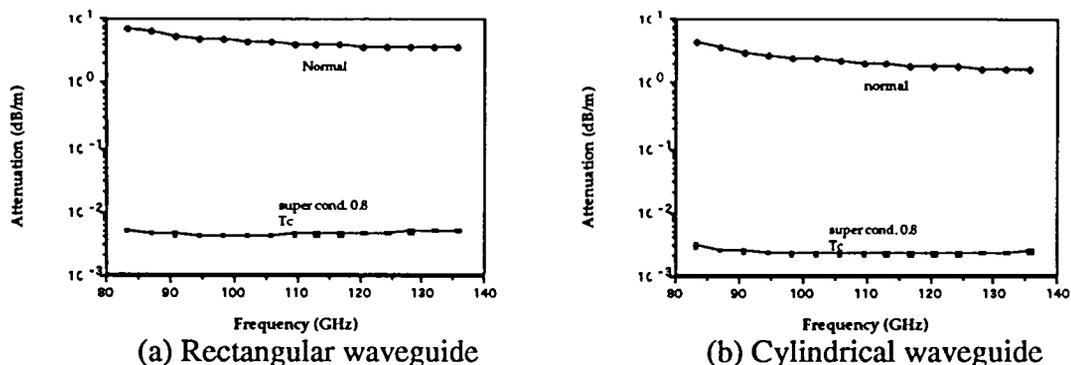


Fig. 5 Attenuation of the superconducting ($T=0.8T_c$) and normal waveguides

The results show that as the temperature increases, the dependence of the waveguide parameters on the frequency is more prominent at higher temperatures.

As we can see from the above calculations, some parameters have to be chosen before the conductivity can be calculated. Even though both approaches are based on the two-fluid model, there is a lack of common basis for the choice of the parameter, this constitutes another difficulty in calculating the conductivity of the superconducting material employing the existing two-fluid model. Our calculations show that although there is no common basis for the choice of the conductivity calculations, the trend of variation of the σ with temperature is similar.

As can be seen, the values of σ obtained are different. At the very least, this seems to point to a certain non-trivial ambiguity that is present in these types of overly phenomenological approaches.

RECOMMENDATIONS FOR IMPROVEMENTS

As seen from the computations, two aspects seem to be clear:

- the usual approximation made in the two-fluid model - relative smallness of the normal electron concentration with respect to the superconducting electron pair concentration - is questionable at temperatures higher than about $0.6 T_c$. Also, the collision-free nature of the superconducting component transport cannot be correct, since there does exist a maximum current at a given temperature; and
- within the two-fluid model, there seem to be differences in terms of the computed parametric values, leading to ambiguities in the choice of appropriate value for the design parameters for the waveguides.

The modifications that seem necessary are:

- a more accurate (velocity-limiting) mechanism for the superconducting current component;

- a more physically acceptable mechanism for transport for electrons in the normal state - the two-fluid model assumes the usual diffusive, weak scattering transport; and
- a consistent set of values for microscopic parameters that are used in the design process of superconducting devices.

ONGOING WORK

Several generalizations and related aspects are being addressed in our group:

- modification of the two-fluid model to include:
 - a more accurate description of the transport process for the normal component σ_n ; and
 - a physically admissible “velocity saturation mechanism” for the superconducting component σ_s ;
- computation of power transmitted and received and the associated dynamic range and bit error rate;
- development of a comprehensive object-oriented database for high T_c superconductors;
- development of an “intelligent design system” for design of superconducting waveguides; and
- development of a circuit simulation program for superconducting circuits.

EMI/EMC OF SUPERCONDUCTING CIRCUITS -A PROPOSAL

This brief section addresses the issue of electromagnetic interference (EMI) and electromagnetic compatibility (EMC) as applied to high T_c superconducting elements and circuits. The intrinsic damping due to electrical resistance in a normal circuit accounts for a major portion of the system EMC. In superconducting circuits, however, such a resistance is close to zero, so that new approaches are needed to determine the conditions under which a system is said to possess a certain minimum degree of electromagnetic compatibility.

Traditionally, the standard approach to the control of electromagnetic effects has been to build the system first, measure the EMI problems and then fix them in a largely empirical way. Our contention is that such a control should be incorporated at the design level. More precisely, the approach taken should be somewhat parallel to that taken during the development of VLSI design, namely that the designers have computer-derived design rules and design-checking programs that give advance warning of problem areas before anything is actually built. Our main goal here consists of seeking to establish such a well-defined procedure for the case of EMI-related problems, viz., minimize EM emissions and susceptibility to external emissions which maximize EM compatibility.

CONCLUSIONS

This paper reported part of the research conducted by our group on the application of existing models and concepts to the design of microwave telecommunications devices. The major conclusions were that: some of the approximations involved in the usual waveguide design are not valid at high frequencies and temperatures close to the transition temperature; and the two-fluid model needs non-trivial modifications for accurate applicability to a real high T_c superconductor.

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