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HIGH FREQUENCY CHARACTERIZATION OF HIGH-TEMPERATURE SUPERCONDUCTING THIN FILM LINES

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Abstract-
An integral equation approach is applied to calculate the propagation characteristics of high temperature thin-film superconducting lines at high frequencies. To evaluate losses in these lines, the superconducting strips are replaced by frequency-dependent surface impedance boundaries. The values of these surface impedances are measured experimentally by a stripline resonator technique. Using this method, phase and attenuation constants as well as characteristic impedance are evaluated and presented as functions of frequency and several other parameters.

INTRODUCTION

A major advantage of high critical temperature superconductors is the reduced surface resistance of the lines as compared to the normally conducting metal strips. These lines are made of thin films which have a thickness large compared to λ, the penetration depth of the magnetic field into the superconductor. Their low-loss properties make them very interesting for most microwave circuits where power loss is usually a limiting factor. Several groups have reported theoretical results for the surface resistance and propagation constant of high T_c films and strips [1],[2],[3],[4]. One common characteristic in all these attempts has been the discrepancies between theoretical and experimental results which in the case of attenuation constant may be of a few orders of magnitude. This disagreement is mainly due to the inadequacy of the implemented theoretical models (London theory or BCS theory) to characterize the electromagnetic behavior of the high T_c superconducting materials as they are presently made.

To avoid the shortcomings of existing theoretical treatments, the presented method does not attempt to solve for the electromagnetic fields inside the superconducting thin films. Only the electric/magnetic field relation on the surface of the strips is utilized to create an equivalent surface impedance boundary which will replace the superconducting strips. Due to the fact that superconducting strips made today have a very large width-to-thickness ratio, the electric/magnetic field ratio on the strip surface is almost identical to the surface impedance of a thin superconducting plane. As a result, measured values of this surface impedance can simulate the superconducting strip very accurately. Having defined an equivalent surface impedance, an integral equation method is developed to solve for the high frequency characteristics of high T_c superconducting thin film strips [5].

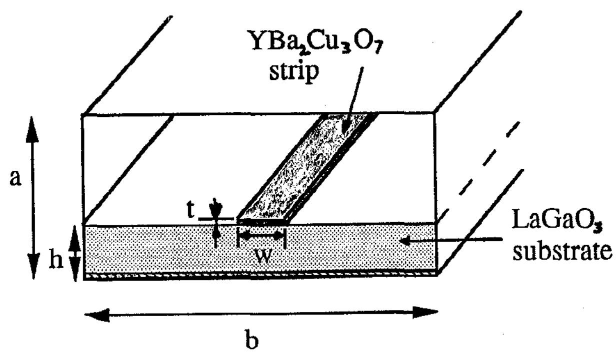


Figure 1: Shielded microstrip line configuration

In this paper, this approach is used to evaluate phase and attenuation constant and characteristic impedance as functions of frequency and other electrical and geometrical characteristics of the superconducting strips and their dielectric substrates.

THEORY

A shielded planar high T_c superconducting line of $YBa_2Cu_3O_7$ film (5000Å) deposited on a $LaGaO_3$ substrate is considered as shown in Figure 1. Dielectric losses in the substrate material are accounted for by assuming a complex permittivity given by:

$$\epsilon_i = \epsilon_{ri}\,(1 - j\tan\delta_i). \qquad (1)$$

The superconducting strip and ground plane are replaced by equivalent surface impedance boundaries with values equal to the experimentally measured surface impedance. With these equivalent boundaries in place, an integral equation for the unknown superconducting current is formulated which is then solved by the method of moments.

Surface Impedance

Using targets composed of Y, BaF_2, and Cu, thin films of $YBa_2Cu_3F_xO_y$ were deposited onto a single-crystal (001) $LaGaO_3$ substrate (1-inch diameter) by magnetron co-sputtering. A detailed description of this approach is reported in [6]. The films were deposited at ambient temperature and were amorphous as deposited. To oxidize and convert the films to the crystalline superconducting phase, they were annealed in wet O_2 at 850^oC for one hour followed by cooling in pure O_2 at $1.5^oC/min.$ $\theta-2\theta$ x-ray diffraction data showed that the annealed superconducting film was highly c-axis and a-axis oriented with only trace amounts of impurity phases, $BaCuO_x$ and CuO_x.

The surface resistance of this film was measured at three different frequencies (22, 86 and 146 GHz) as a function of the temperature using the same experimental technique [7]. This film was also measured using a stripline resonance technique where the surface resistance was determined at $4.2K$ [8]. In both studies the ω^2 dependence was verified and is consistent with BCS theory and with experimental measurements on conventional low T_c superconductors. As it has been found, the surface resistivity varies from approximately 1 mΩ at 4.2 K to 10 mΩ at 70 K for a frequency of 22 GHz. In situ grown films of $YBCO$ of approximately the same thickness have been found to have significantly lower resistance, as low as $0.1m\Omega$ at $4K$ at a frequency of 1 GHz [9].

The surface reactance behaves as purely inductive and varies linearly with frequency as has been reported by many authors [10],[11],[12]. The value of this inductance for the superconducting strips considered here has been measured experimentally by A.T. Fiory using a two-coil mutual-inductance measurement technique [11].

In view of the above the surface impedance used in our theoretical derivations is given by:

$$Z_{sc}(f,T) = R_{sc}(f,T) + jX_{sc}(f,T) \tag{2}$$

where $R_{sc}(f,T)$ represents the Joule losses and $X_{sc}(f,T)$ represents the inductive energy stored within the superconductors. In Equation (2), R_{sc} and X_{sc} are given by

$$R_{sc}(f) = 2.066 \times 10^{-6} f^2 \tag{3}$$

and

$$X_{sc}(f) = 2\pi f L_{sc} \tag{4}$$

where f is in GHz. For $YBa_2Cu_3O_7$ film at 77 K, the value of L_{sc} is about 2 pH at $f = 10$ kHz. Therefore, X_{sc} is given by

$$X_{sc}(f) = 4\pi 10^{-3} f. \tag{5}$$

The dielectric material used for these films has shown only a weak temperature-dependent permittivity which has a value of 22 at 20 GHz. However, the loss tangent of this material varies with temperature from 5.0×10^{-6} at 4.2 K to 10^{-4} at 77 K [13].

Superconducting Current

The surface impedance discussed previously describes the frequency-dependent field penetration in the superconductors and is applied as a boundary condition for the electromagnetic fields excited between the thin-film strips and the ground. The resulting integral equation to be solved is given by:

$$\int \{\bar{\bar{\Gamma}}(x/x') \,.\, \bar{J}\, dy' \; - \; \bar{\bar{Z}}_{sc} \,.\, \bar{J}\,\} \,|_{k_z = k_z^{MS}} = 0 \tag{6}$$

where $\bar{\bar{\Gamma}}$ is the dyadic green's function for the pertinent boundary value problem, $\bar{J}$ is the superconducting current flowing in the strips and $\bar{\bar{Z}}_{sc}$ is a dyad representing the equivalent impedance boundary. This dyad is given by the following expression:

$$\bar{\bar{Z}}_{sc} = Z_{sc}\, \hat{y}\hat{y} \; + \; Z_{sc}\, \hat{z}\hat{z} \tag{7}$$

The integral equation in (6) is solved numerically as explained in [5] to give the complex propagation constant. The characteristic impedance of the superconducting lines is then evaluated from the conventional power-current relation.

RESULTS

Using the approach described in the previous section a computer program was developed to calculate the complex propagation constant, current distribution and characteristic impedance of superconducting lines. The validity of this program has been verified in the case of lossy regular conducting strips where the achieved accuracy was better than 2% [5].

Throughout this section, unless otherwise noted, it is assumed that the structure has the geometry shown in Figure 1, where the dielectric substrate has $\epsilon_r = 22$, $\tan\delta = 5.0 \times 10^{-5}$, $h = 0.5$ mm and the line is 250 μm wide at an operating frequency varying from 500 MHz to 10 GHz. The line is assumed to have a nominal surface resistance of 1 mΩ. The operating temperature is taken to be well below the critical temperature T_c of the superconducting thin film.

Sensitivity studies are performed to analyze the effect of various parameters on the propagation characteristics of the lines. The most important parameters in the electromagnetic characterization of these lines are temperature, line width and substrate thickness.

Temperature Variation

As it has been discussed earlier, when the temperature varies from 4 K to 70 K, both R_{sc} and loss tangent vary while ϵ_r and L_{sc} remain unaffected. In addition, it has been observed that losses due to the nonzero conductivity of the superconducting strips are overshadowed by dielectric losses in the dielectric substrate. In order to study the effect of temperature on both power loss mechanisms, the superconducting surface resistance and the loss tangent were varied independently. Figure 2a shows the effect of $tan\delta$ and frequency variation on the attenuation constant α for a 250 μm superconducting line while R_{sc} was kept constant to 1 mΩ. The changes in α reflect the effect of temperature on the dielectric losses of the 20 mils $LaGaO_3/LaAlO_3$ substrate.

Figure 2b shows the effect of superconducting surface resistivity and frequency variation on the attenuation constant α for a superconducting line on a 20 mils $LaGaO_3/LaAlO_3$ substrate. The loss tangent of the material was kept constant to 5×10^{-5}. The changes in α reflect the effect of temperature on the superconducting losses of a 250 μm superconducting line over an infinite superconducting ground.

Strip Width and Substrate Thickness Variation

The propagation characteristics of the superconducting line are then studied as a function of the height of the substrate and the line width (Figure 3). The phase constant strongly depends on both parameters. Dispersion is more pronounced as the width of the strip and thickness are increased. For thin substrates, dispersion only happens at much higher frequencies. The attenuation constant varies inversely to the height of the substrate and width of the line. The characteristic impedance follows the same trend as in the case of lossless lines and shows very little dispersion over the frequency range studied here.

The main goal of this sensitivity study is to give a qualitative understanding of the effect of temperature, frequency, line width and substrate thickness on the superconducting and dielectric losses associated with thin-film lines printed on $LaGaO_3/LaAlO_3$ substrate. Results will also be presented for the case of two and three dimensional structures (such as filters and resonators) and extensive comparisons with measurements will be made.

CONCLUSIONS

A generalized integral equation approach is used to calculate the propagation constant of superconducting thin film strips. An equivalent impedance boundary is employed that simulates the electromagnetic behavior of the superconductors. Phase constant, attenuation and characteristic impedance are presented for different values of the superconducting surface resistance and line strip width as well as loss tangent and thickness of the substrate material.

ACKNOWLEDGMENTS

This work was supported by the Army Research Office under contract project DAAL03-K-0088(23836-EL).

References

[1] J.M. Pond, C.M. Krowne, W.L. Carter, "On the Application of Complex Resistive Boundary Conditions to Model Transmission Lines Consisting of Very Thin Superconductors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, No. 1, pp 181-190, January 1989.

[2] A.C. Cangellaris, "Propagation Characteristics of Superconductive Interconnects," *Microwave and Optical Tech. Letters*, vol. 1, No. 5, pp 153-156, July 1988.

[3] O.K. Kwon, B.W. Langley, R.F.W. Pease, M.R. Beasley, "Superconductors as Very High-Speed System-level Interconnects," *IEEE Electron Device Letters*, vol. EDL-8, No. 12, pp 582-585, December 1987.

[4] H.Y. Lee, T. Itoh, "Phenomenological Loss Equivalence Method for Planar Quasi-TEM Transmission Lines with a Thin Normal Conductor or Superconductor," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, No. 12, December 1989.

[5] T.E. van Deventer, P.B. Katehi, A.C. Cangellaris, "An Integral Equation Method for the Evaluation of Conductor and Dielectric Losses in High Frequncy Interconnects," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, No. 12, December 1989.

[6] J.Y. Josefowicz, D.B. Rensch, A.T. Hunter, F. Krajenbrink, R. Miles, to be published.

[7] D.W. Cooke, E.R. Gray, R.J. Houlton, B. Rusnak, E.A. Meyer, J.G. Beery, D.R. Brown, F.H. Garzon, I.D. Raistrick, A.D. Rollet, R. Bolmaro, submitted to Appl. Phys. Lett.

[8] D.E. Oates, A.C. Anderson, "Stripline Measurements of Surface Resistance Relation to HTSC film Properties and Deposition Methods", *presented at SPIE*, Santa Clara, CA, October 1989.

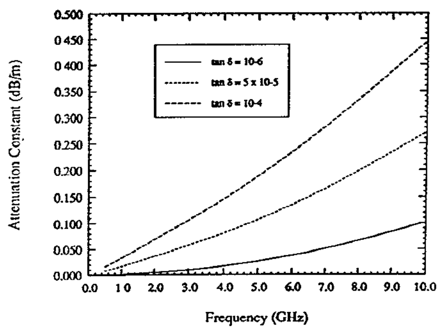
[9] L. Drabeck, G. Gruner, J.J. Chang, A. Inam, X.D. Wu, L. Nazar, T. Venkatefan, D.J. Scalapino, " Millimeter-Wave Surface Impedance of $YBa_2Cu_3O_7$", *Physical Review B*, vol. 40, No. 10, p 7350, October 1989

[10] H. Chaloupka, G. Muller, U. Klein, H. Piel, "New Experimental Results for Microwave Conductivity of High-T_c Superconductors and Consequences for Applications to Linear Devices," *IEEE MTT-International Symposium Digest*, pp 547-550, June 1989.

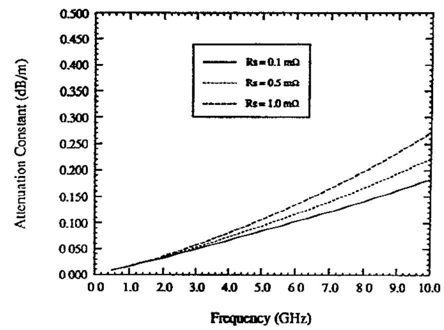
[11] A.T. Fiory, A.F. Hebard, P.M. Mankiewich, R.E. Howard, "Penetration Depths of High T_c Films measured by Two-Coil Mutual Inductances," *Applied Physics Letters*, vol. 52, No. 25, pp 2165-2167, 20 June 1988.

[12] L.A. Hornak, M. Hatamian, S.K. Tewksbury, E.G Burkhardt, "Experiments with a 31-cm High-T_c Superconducting Thin Film Transmission Line," *IEEE MTT-International Symposium Digest*, pp 623-626, June 1989.

[13] R.L. Sandstrom, E.A. Giess, W.J. Gallagher, A. Segmuller, E.I. Cooper, M.F. Chisholm, A. Gupta, S. Shinde, R.B. Laibowitz, *Applied Physics Letters*, vol. 53, pp 1874, 1988.

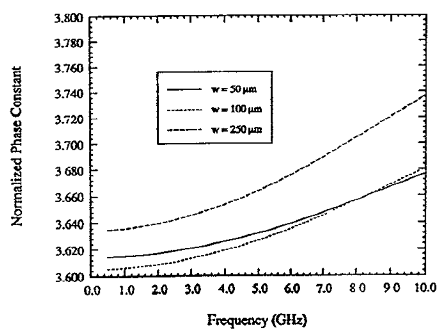


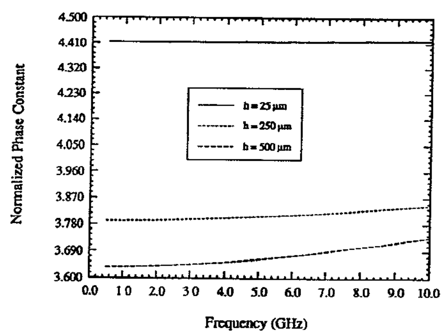
a. Attenuation constant vs. frequency for $tan\delta = 10^{-6}$, 5 10^{-5}, 10^{-4}



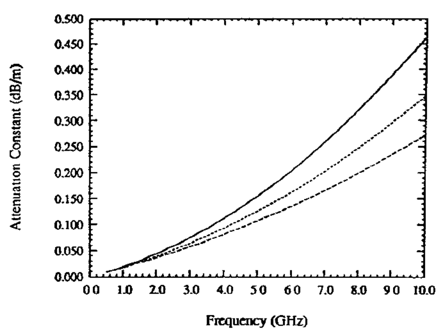
b. Attenuation constant vs. frequency for $R_s = 0.1$, 0.5 and 1 mΩ

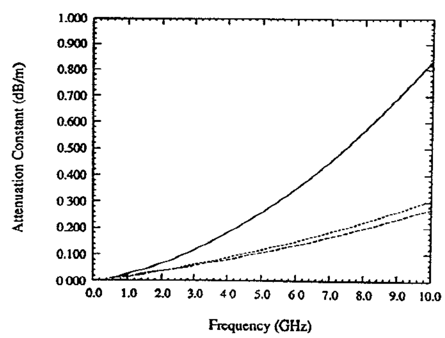
Figure 2: Effect of electrical parameters on the attenuation constant of the dominant microstrip mode as a function of frequency ($\epsilon_r = 22$, $w = 250$ μm, $h = 0.5$ mm)



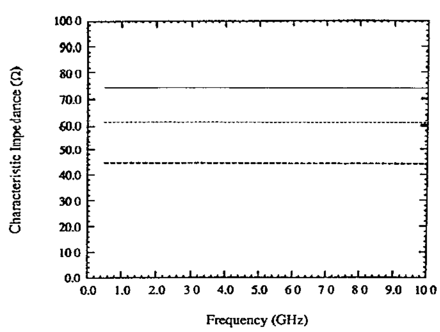


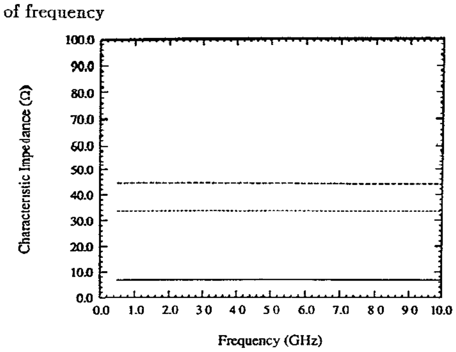
a. Phase constant as a function of frequency





b. Attenuation constant as a function of frequency





c. Characteristic Impedance as a function of frequency

Figure 3: Effect of width and height on the propagation characteristics of the dominant microstrip mode ($\epsilon_r = 22$, $\tan\delta = 5$ x 10^{-5}, $R_s = 1$ mΩ)