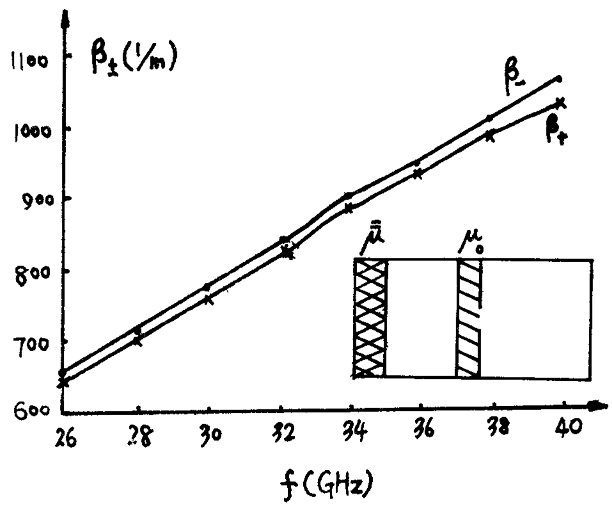

Fig 4 Numerical results: $2a = 7.112$ mm, $2b = 3.556$ mm, $d = 0.125$ mm, $w/b = 0.1$, $h = 1.0$ mm.

propagation constants and $(\beta_- - \beta_+)$ become smaller. Our computational results show that when the thickness of the ferrite substrate is larger than 1.0 mm β_+ and β_- increase very slowly. If the loss of ferrite materials is considered in designing isolators, the optimum thickness of the ferrite should be 1.0–1.2 mm.

From Fig. 4, we can see that when the ferrite substrate is located to the short side of the waveguide, the propagation constants and $(\beta_- - \beta_+)$ become smaller. This is because the propagating fields are concentrated in the neighborhood of the slot, and as the frequencies become larger the fields are more concentrated near the slot [8]. Other advantages of finline isolators are discussed in the literature [9].

Our computational results also show that as the thickness of dielectric substrates increases, the propagation constants and $(\beta_- - \beta_+)$ decrease.

V. Conclusions

The admittances of TM and TE modes in ferrite substrate are given by applying Maxwell's equations and Fourier transforms. The unilateral finline with magnetized ferrite substrate has been analyzed using the equivalent transmission line concept in the spectral domain in conjunction with Galerkin's method. Numerical results for propagation constants have been obtained and compared with the results available in the literature [2]. The results of forward and backward propagation constants are very useful in designing a displacement isolator with good quality. The field or power distributions are the most important information in designing a displacement type isolator. The author is currently investigating this, and the results will be reported in the near future.

Acknowledgment

The author wishes to thank Prof. K. J. Rao of the University of Electronic Science and Technology of China for his support and encouragement. The author dedicates this paper to his wife and daughter.

References

[1] A. Beyer and I Wolff, "A finline ferrite isolator and circulator for the *R*-band," presented at the 11th European Microwave Conf, Amsterdam, 1981

[2] A. Beyer and I Wolff, "Design of a millimeter-wave ferrite isolator at 28.5 GHz," *Proc. Inst. Elec Eng.*, pt. H, vol. 132, pp. 244–250, July 1985.

[3] T. Itoh, "Spectral domain immittance approach for dispersion characteristics of generalized printed transmission line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 733–736, July 1980.

[4] A. G. Gurevich, *Ferrites at Microwave Frequencies*. New York: Consultants Bureau, 1963.

[5] L. P. Schmidt, T. Itoh, and H. Hofmann, "Characteristics of unilateral finline structures with arbitrary located slots," *IEEE Trans. Microwave Theory Tech*, vol. MTT-29, pp. 352–355, Apr 1981

[6] L. P. Schmidt and T. Itoh, "Spectral domain analysis of dominant and higher order modes in fin-line," *IEEE Trans. Microwave Theory Tech.*, vol MTT-28, pp. 981–985, Sept. 1980.

[7] P. J. Xun, "The propagation constants of unilateral fin-line with magnetized ferrite substrate," presented at the Second Asia–Pacific Microwave Conf, Beijing, 1988.

[8] P. J. Xun, "Discrete Fourier transform for the field distributions of fin-line," *J. Univ. Electron. Sci. Technol. China*, to be published.

[9] A. Beyer and K. Solbach, "A new fin-line ferrite isolator for integrated millimeter-wave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1344–1348, Dec. 1981

Microstrip Ring Resonator Technique for Measuring Microwave Attenuation in High-T_c Superconducting Thin Films

JUNE H. TAKEMOTO, STUDENT MEMBER, IEEE, FLOYD K. OSHITA, STUDENT MEMBER, IEEE, HAROLD R. FETTERMAN, SENIOR MEMBER, IEEE, PAUL KOBRIN, AND EMILIO SOVERO, MEMBER, IEEE

Abstract—Microwave attenuation of high-T_c superconducting (HTS) films sputtered on MgO and ZrO_2 were measured using a microstrip ring resonator circuit. The results of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O resonators were compared to gold-plated resonators of identical design. The losses of superconducting and gold-plated films were determined from unloaded Q-factor measurements. The attenuation of Y-Ba-Cu-O film on a MgO substrate is approximately 31 percent lower than gold films at 6.6 GHz and 33 percent lower at 19.2 GHz for temperatures below 50 K. The approach of using microstrips to characterize microwave losses shows the usefulness of HTS films in integrated circuit technology.

I. Introduction

The recent discovery of high-T_c superconductors (HTS's) has drawn considerable attention towards the possibility of using thin films in microwave integrated circuits. Zero dc resistivity and reduced microwave attenuation give HTS performance advantages over devices and circuits fabricated with conventional gold conductors. Numerous high-frequency measurements have been reported which characterize these new oxide superconductors at microwave and millimeter-wave frequencies using high-Q cavity resonators [1], [2] and stripline resonators [3]. In this paper we report results on microwave attenuation in Y-Ba-Cu-O (YBCO) and Bi-Sr-Ca-Cu-O (BSCCO) superconductors based on Q-factor measurements of microstrip ring resonators. To our knowledge this is the first reported implementation of superconducting microstrip, which demonstrates the applicability of fabricating

Manuscript received January 13, 1989; revised April 25, 1989

J. H. Takemoto was with the Electrical Engineering Department, University of California at Los Angeles, Los Angeles, CA 90024. She is now with TRW, MS R1/2170, One Space Park, Redondo Beach, CA 90278

F. K. Oshita and H. R. Fetterman are with the Electrical Engineering Department, University of California at Los Angeles, Los Angeles, CA 90024.

P. Kobrin and E. Sovero are with the Rockwell Science Center, Thousand Oaks, CA 91360

IEEE Log Number 8929928.

HTS thin-film structures using integrated circuit processing techniques.

II. Ring Resonators

Microstrip resonators have been used extensively to study dispersion, the effective dielectric constant, and microwave attenuation on dielectric substrates. The most widely used resonators are the ring resonator and the open-ended linear resonator. The disadvantage of open-ended linear resonators is the considerable radiative losses from the open ends, which can seriously complicate the determination of microstrip conductor losses. The closed-loop ring resonator, however, has no open-end effects, so the attenuation sources result primarily from dielectric and conductor losses [4].

The design of a ring resonator requires optimization of the coupling gap size, the impedance of the ring, the harmonic mode, and the dielectric material in order to obtain satisfactory experimental results. The gap size determines the amount of RF coupling of the ring, which affects the feasibility of evaluating the unloaded Q from swept frequency measurements. The diameter of the ring is given by $D_0 = n\lambda_g/\pi$, where λ_g is the guide wavelength and n is the harmonic mode. Finally, two factors must be considered in selecting a suitable substrate: 1) the crystal structure of the substrate should promote the growth of high-quality perovskite HTS films, and 2) the dielectric constant and loss tangent should be low enough that dielectric loss does not dominate the measured response.

III. Fabrication and Testing

The samples tested had a mean diameter of 213 mils, a ring width of 20 mils, a conductor thickness of 1 μm for YBCO and 1/2 μm for BSCCO, and a substrate thickness of 20 to 30 mils. The chosen dielectric substrates were MgO and ZrO_2, with dielectric constants of 10 and 8, respectively. The microstrip input lines were designed to match the standard 50 Ω impedance of the RF power source. A dc resistivity strip was included to monitor the dc transition of the thin film. The superconducting thin films which gave the best results were sputtered on MgO at 700°C for YBCO and 20°C for BSCCO by the Rockwell Science Center (Thousand Oaks, CA). The samples were then annealed at 850°C in oxygen for YBCO and at 880°C for BSCCO samples. The critical current density of the films on MgO were typically of the order of 10^6 A/cm^2 for YBCO and 10^5 A/cm^2 for BSCCO at 10 K [5]. Ring resonator patterns were printed onto the films by using standard semiconductor photolithographic techniques. Etching of unwanted films was done by argon ion milling. Due to difficulties encountered with the fabrication of superconducting thin films on both sides, a plated gold layer was used for the microstrip ground plane. As a comparison, identical gold-plated ring resonators were also fabricated.

The test system configuration consisted of a closed-cycle He refrigerator in which the resonator sample was mounted on a test fixture and attached to the cold finger. The difference in the sharpness of the reflection responses taken by the network analyzer in Fig. 1 illustrate the increase in Q of the YBCO on MgO resonator below its T_c of 72 K.

IV. Analysis

From swept frequency reflection measurements, the unloaded Q is calculated [6]. The unloaded Q is derived from the reflection-amplitude response taken from either port of the resonator. The unloaded Q of a microstrip resonator is related to the

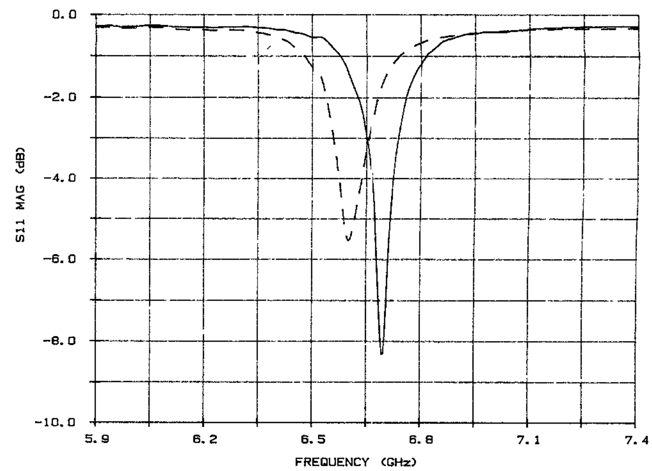

Fig. 1. Amplitude-reflection response of a YBCO on MgO resonator at 67 K (dashed line) and 40 K (solid line) plotted from the network analyzer.

various loss mechanisms in a microstrip line:

$$1/Q_t = (\lambda_g/\pi) * (\alpha_c + \alpha_d) + 1/Q_r \tag{1}$$

where α_c and α_d are the conductor and dielectric loss constants in Np/m, λ_g is the guide wavelength, and Q_r is the radiation quality factor [7]. The conductor loss constant α_c is estimated from the expression

$$4\pi\alpha_c Z_0 = B[(C+D)R_{S1} + CR_{S2}] \tag{2}$$

where

$$B = 1 - w'^2/(16h^2)$$
$$C = (1/h)[1 - t/(\pi w')]$$
$$D = (2/w')[1 + (1/\pi)\ln(2h/t)]$$
$$w' = w + (t/\pi)[\ln(2h/t) + 1]$$

and Z_0 is the characteristic impedance, R_{S1} and R_{S2} are the surface resistivities of the strip and ground plane metallization, and w', w, h, and t are the effective electrical microstrip width, actual ring width, substrate height, and film thickness, respectively. [8].

In order to separate out the loss contribution due to a gold ground plane in the superconducting sample, (1) and (2) are combined to yield an expression for the surface resistivity R_{ss} of the superconductor:

$$R_{ss} = R_{sa} - \left[4\pi^2 Z_0/(\lambda_g B(C+D))\right] * (1/Q_a - 1/Q_s) \tag{3}$$

where Q_a is the measured unloaded Q of the standard gold resonator, Q_s is the measured unloaded Q of the superconductor sample with the gold ground plane, and R_{sa} and R_{ss} are the surface resistivities of plated gold and thin film superconductor, respectively. Once R_{ss} is obtained, the conductor attenuation α_{css} and unloaded Q_{ss} in an ideal sample with superconductors on both sides can be calculated.

V. Results and Conclusions

The YBCO and BSCCO samples had transition temperatures of 72 K nd 69 K, respectively. A comparison of the unloaded Q versus temperature for both the gold and YBCO samples is shown in Fig. 2. The unloaded Q obtained from the YBCO sample is higher than the gold sample by 39 percent at 6.6 GHz and 42 percent at 19.2 GHz at 40 K. Since the superconducting

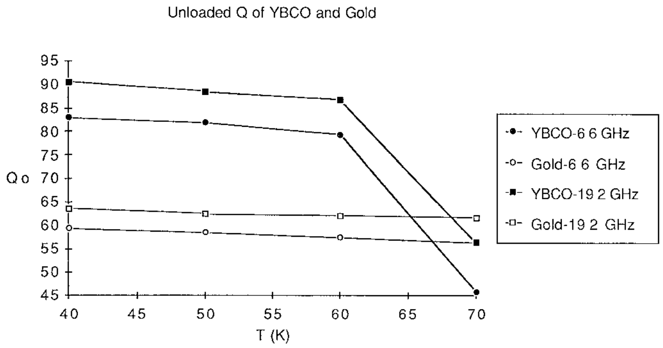

Fig. 2. Plot of unloaded Q versus temperature shows the high frequency transition below T_c for the YBCO on MgO resonator. The superconductor is better than gold below 50 K by about 40 percent.

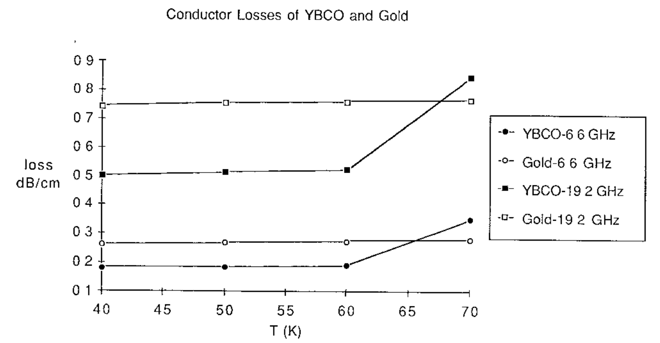

Fig. 3. Plot of conductor attenuation versus temperature shows that YBCO has lower loss than gold by about 32 percent on the MgO substrate.

sample was fabricated with a gold ground plane, a higher Q is expected for a superconducting ground plane.

Fig. 3 plots the temperature dependence of conductor attenuation α_c for the gold and YBCO samples. The conductor loss for YBCO is lower than gold by 31 percent at 6.6 GHz and 33 percent at 19.2 GHz at 40 K. The sharp rise in Q below T_c is qualitatively consistent with the two-fluid model. The relatively high attenuation and surface resistivity in both the gold and superconductor can be attributed to the fact that the film thickness is comparable to skin depth of the materials. Other factors could be the intergranular coupling and the anisotropic nature of the ceramic superconductors, which do not provide a good conducting path for high frequencies. The BSCCO sample was measured to have a slightly higher conductor loss than gold. The YBCO films grown on ZrO_2 substrates which were fabricated by another company did not yield films with low enough surface resistivity. The higher losses of these samples could be attributed to the degree of c-axis orientation of the films [9].

Preliminary studies on resonators with superconductors on both sides of the dielectric have been performed. Presently, the unloaded Q and conductor losses are close to the superconducting sample with the gold ground plane. Development of double-sided fabrication of HTS samples will further enhance the usefulness of HTS thin films to microstrip applications.

The results of this study have shown that the microwave performance of highly oriented films of HTS is better than conventional gold conductors. Also, the use of microstrips to measure the microwave losses demonstrates the capability of HTS films to be directly implemented into integrated circuits. Understanding how the processing of HTS thin films can be developed to promote low microwave attenuation is essential to the success of superconducting microstrip circuits [10].

Acknowledgment

The authors would also like to thank K. Daly, R. Simon, and A. Silver of TRW for their support in Ar ion milling and fabricating YBCO on ZrO_2 and MgO substrates. Also, they would like to thank M. Matloubian for his invaluable ideas and suggestions.

References

[1] J. S. Marten, J. B Beyer, and D. S. Ginley, "Microwave surface resistance of $YBa_2Cu_3O_{6\,9}$ superconducting films," *Appl. Phys. Lett.*, vol. 52, no. 21, pp. 1822–1824, May 1988.

[2] J. P. Carini *et al.*, "Millimeter-wave surface resistance measurements in highly oriented $YBa_2Cu3O_{7-\delta}$ thin films," *Phys. Rev B*, vol 37, no. 16, pp. 9726–9729, June 1988

[3] M. S. DiIorio, A. C Anderson, and B Y. Tsaur, "rf surface resistance of Y–Ba–Cu–O thin films," *Phys. Rev B.*, vol. 38, no. 10, pp. 7019–7022, Oct. 1988.

[4] T. C. Edwards, *Foundations for Microstrip Circuit Design.* New York: Wiley, 1981, pp. 184–186.

[5] W. Ho *et al*, "Millimeter-wave complex conductivity measurements of Bi–Sr–Ca–Cu–O superconducting thin films," *Phys. Rev. B*, vol. B38, pp. 7029–7032, Oct. 1, 1988.

[6] J. Aitken, "Swept-frequency microwave Q-factor measurements," *Proc. Inst. Elec. Eng.*, vol. 123, no. 9, pp 855–862, Sept 1976

[7] A. Gopianth, "Maximum Q-factor of microstrip resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 128–131, Feb. 1981

[8] R. A Pucel, D. J Masse, and C. P. Hartwig, "Losses in microstrip," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 342–350, June 1968; Correction, vol. MTT-16 pp. 1064, Dec 1968.

[9] T. L. Hylton *et al.*, "Weakly coupled grain model of high frequency losses in high T_c superconducting thin films," *Appl. Phys. Lett.*, vol. 53, no. 14, pp 1343–1345, Oct 1988.

[10] N. Klein *et al*, "Millimeter wave surface resistance of epitaxially grown $YBa_2Cu_3O_{7-x}$ thin films," *Appl Phys Lett*, vol. 54, no. 8, pp 757–759, Feb. 1989.

Determination of the Cutoff of the First Higher Order Mode in a Coaxial Line by the Transverse Resonance Technique

HARRY E. GREEN, SENIOR MEMBER, IEEE

Abstract—**This paper uses the transverse resonance technique and static field considerations to determine cutoff for the first higher order mode in a coaxial line. The result, while approximate, agrees very well with the rigorous field-theory solution for all practical coaxial lines. The solution also has an immediate connection with the physics of the problem which makes the result obtained almost obvious.**

I. Theoretical Development

In [1] the transverse resonance technique is developed to permit determination of cutoff in waveguides having doubly connected cross sections. The method relies on inserting a reference

Manuscript received September 7, 1988; revised April 12, 1989.
The author is with the Surveillance Research Laboratory, Defence Science and Technology Organisation, P.O. Box 1650, Salisbury, S A 5108, Australia.
IEEE Log Number 8929891.