A COPLANAR WAVEGUIDE FILTER USING THIN-FILM HIGH TEMPERATURE SUPERCONDUCTOR

Wilbert Chew, Louis J. Bajuk, Thomas W. Cooley, Marc C. Foote, Brian D. Hunt, Daniel L. Rascoe, and A. Landis Riley

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

The design of a coplanar waveguide low-pass filter made of high critical temperature superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) film on a $LaAlO_3$ substrate is described. The patterned and packaged coplanar waveguide low pass filter of YBCO exhibited measured insertion losses in liquid nitrogen superior to the loss of a similar thin-film copper filter throughout the 0 to 9.5 GHz passband. Coplanar waveguide models for use with thin film normal metal (with thickness either greater or less than the skin depth) and YBCO are discussed and used to compare the losses of the measured YBCO and copper circuits.

INTRODUCTION

High critical temperature (high T_c) superconductors, fabricated as high-quality aligned films on suitable substrates, can now be used to make low-loss thin-film microwave circuits. Coplanar waveguide (CPW) is a particularly convenient thin film structure requiring only one side of a substrate to be coated with superconductor, allowing the other side to be thermally anchored during deposition and in-situ annealing of the superconductor. CPW resonators made of $YBa_2Cu_3O_{7-\delta}$ (YBCO) have shown losses superior to copper at 77 K.[1] We have made CPW low-pass microwave filters of YBCO on $LaAlO_3$ substrates which exhibit losses lower that those of comparable copper or silver filters at 77 K [2], by 0.4 dB at 0.5 GHz to as much as 1.7 dB at 9.5 GHz.

These 0-9.5 GHz passband filters consisted of sections of CPW transmission lines having dimensions suitable for integrated circuits. The filter design, shown in Fig. 1, consisted of tapered microstrip-to-CPW transitions at the input and output, 50 ohm CPW transmission lines near the input and output, and alternating low and high impedance CPW transmission line sections. The substrate was 10 mm x 10 mm x 0.5 mm $LaAlO_3$. The design line widths and lengths are given in Table 1. Further structure and fabrication details are given in Reference 2. The relatively narrow line widths and large area used for the filter provide a stringent test of the usefulness and practicality of currently available YBCO. Similar segments of transmission lines made of thin film superconductors can be used to make a broad range of microwave circuits, as well as low-loss and low dispersion interconnections for integrated circuits.

DESIGN

The effective permittivity and step discontinuity effects were evaluated using the CPW test structures of Fig. 2, fabricated in 1 μm thick silver film on $LaAlO_3$. The S-parameters of these test structures were measured using a standard commercial wafer probe and microwave network analyzer. The test structures were modeled using the commercial microwave CAD software EEsof Touchstone™ as cascaded lengths of transmission line. A step discontinuity was simply modeled as a variable extra length of the wider line with an equal lessened length of the narrower line at each kind of step. Another variable was the effective permittivity. Using the software to optimize the fit of the measured data to the model data by adjusting the variables gave approximate extra effective lengths of 17 μm for the 200 μm lines at junctions with 50 μm lines and 18 μm for the 200 μm lines at junctions with 10 μm lines, and an effective relative permittivity of 12.8 for the CPW lines (or a relative permittivity of approximately 25 for $LaAlO_3$. An empirical expression was used for the attenuation constant α_n of a normal metal line as a function of frequency f, where thickness could be greater or less than the skin depth:

$$\alpha_n = \alpha_{n0} (f/f_0)^{1/2} + \alpha_{n1} \quad (1)$$

where f_0 is a reference frequency, and α_{n0} and α_{n1} are adjustable parameters. α_n's for each line width are different, and were chosen to have the same ratios as predicted using formulas for shallow field penetration. Because the effect of attenuation in the narrow 10 μm wide lines dominated the effects of attenuation in the wider lines, more exact values were not needed for the design. Further analysis discussed later does give approximate results for all the lines in a consistent way using a single adjustable parameter.

After determining the step model and the permittivity, a test filter was designed, assuming no loss, by using Touchstone™ to optimize the design line lengths for the desired low-pass response. Both silver and YBCO versions were fabricated and mounted in test fixtures on copper blocks dipped in liquid nitrogen; their S-parameters were measured to assess the effects of YBCO compared to silver. The silver film filter showed performance consistent with the modeled design.

A circuit model for the YBCO test filter consisted of sections of general transmission line like the circuit model for the silver filter, except for a different empirical loss model and a factor to model the effect of the increased inductance, which affects the phase velocity v as well as the impedances of the transmission line sections. For a general transmission line with an inductance/length L, capacitance/length C, and low losses (low series resistance/length R and low shunt conductance/length G_L) the phase velocity v and characteristic impedance Z are: [3]

$$Z = \sqrt{\frac{R+j\omega L}{G_L+j\omega C}} \approx \sqrt{L/C} \quad [\Omega] \quad (2)$$

$$v \approx 1/\sqrt{LC} \quad (3)$$

Thus, the increased inductance was modeled as a factor K which decreased the phase velocity and increased the characteristic impedance of each section of transmission line:

$$v \approx v_0 / K, \quad Z \approx KZ_0 \quad (4)$$

$$\textit{where} \quad K=\sqrt{L/L_e},\ v_0=1/\sqrt{L_eC},\ Z_0=\sqrt{L_e/C} \quad (5)$$

L is the total inductance/length, and L_e is the "external" inductance/length of the transmission line excluding contributions from within the conductor. (The effective permittivity of the general transmission line element was used to control the phase velocity on the transmission line in the CAD software.) Further analysis discussed later indicates that the increased inductance effect is concentrated in the narrow line sections, but assuming an average wave-slowing factor for the entire filter was adequate for the minor design change necessary to get the desired passband. The superconducting attenuation was assumed to increase with the square of the frequency:

$$\alpha_{SC} = \alpha_{SC0}\,(f/f_0)^2 \quad (6)$$

where α_{SC0} is an adjustable parameter and f_0 is a fixed reference frequency. K and α_{SC0} were found by optimizing the fit of the model to the measured S-parameters for the YBCO filter. These values were then used to design the final deliverable filters.

RESULTS

The deliverable filters, using in-situ annealed films, were patterned by argon ion milling, as described in Reference 2. No post-annealing was done after patterning. The patterned line widths were narrowed by approximately 4 µm from the design widths listed. The average YBCO film thickness was 0.5 µm. Critical current and T_c measurements were made on the patterned filters to select those suitable for assembly. (Good filters had T_c > 83 K and critical current density $J_c > 4\times10^5$ A/cm^2 at 77 K; the best had T_c = 87.8 K and $J_c=8.1\times10^5$ A/cm^2.)

The performance of the YBCO filters was measured after all processing, patterning, assembly, and welding of the package in vacuum were completed. Measured transmission ($|S_{21}|$) is shown in Fig. 3 for 4 YBCO filters, along with that for a filter made using 1 µm thick copper film, all at 77 K. For comparison, the transmission of the copper filter at 297 K is also shown. The YBCO CPW filter responses exhibited lower loss throughout the passbands of the filters, compared to the cooled copper filter (by as much as 1.7 dB at 9.5 GHz). The superiority of YBCO over copper would be greater at lower temperatures.

ANALYSIS

The "Phenomenological Loss Equivalence Method" (PEM) of Lee & Itoh [4],[5],[6] allows a more consistent analysis than the purely empirical formulas used to model attenuation in the original design. In this model, in addition to the usual (external) impedance calculated from fields around perfect conductors, an internal impedance/length Z_i from fields penetrating into the conductor is included [4]:

$$Z_i = R_i + j\,\omega\,L_i = Z_s\,G\,\coth[Gwt\sqrt{j\omega\mu\sigma}\,] \quad (7)$$

where R_i is the real part of Z_i, L_i is the internal inductance/length, ω is the radian frequency, μ is the permeability, σ is the complex conductivity of the conductor, coth is the hyperbolic cotangent, w is the width of the center conductor in CPW, t is the thickness of the conductor, Z_s is the characteristic surface impedance of the conductor used and is defined by

$$Z_s \equiv \sqrt{j\omega\mu/\sigma} \quad [\Omega/\text{square}] \quad (8)$$

G is a geometric factor [4] which was approximated by

$$G \approx \left(\frac{\sqrt{\epsilon_{eff}}}{\eta_0}\right)\cdot\frac{[Z_0(w,t,g) - Z_0(w-2\Delta,t-2\Delta,g+2\Delta)]}{\Delta} \quad (9)$$

where η_0 is the characteristic impedance of free space (377 Ω), ϵ_{eff} is the effective relative permittivity for the CPW transmission line, g is width of the CPW gaps, Δ is an incremental distance with $\Delta << w,t$. $Z_0(w,t,g)$ is the "external" impedance, which is the usual impedance calculated for CPW, but includes the effect of a thick (but perfect) conductor. $Z_0(w,t,g)$ was found using formulas given by Gupta et al.[7] which have been tested for use in the PEM formula by Kong et al.[6]

Once R_i and $j\omega L_i$ in eqn. (7) are found, the general transmission line model (eqns. 2-5) can be used with

$$R = R_i \quad \textit{and} \quad L = L_e + L_i \quad (10)$$

(C is assumed the same as the usual "external" value) giving the usual transmission line result [3]

$$\alpha_{dB} = 8.686\cdot\alpha \approx \frac{8.686\cdot R_i}{2\sqrt{L/C}} \quad (11)$$

where α is the attenuation in neper/length, and α_{dB} is the attenuation in dB/length.

Using these expressions for α and the internal inductance effects in the transmission line sections of the CAD models for the filters, the filter circuit models were fit to the data with only σ_{Cu} and the real and imaginary parts of σ_{YBCO} as freely adjustable parameters. The normal metal conductivity σ_{Cu} was assumed to be a constant with respect to frequency, while the superconductor conductivity was assumed to have the form

$$\sigma_{YBCO} = \sigma_1 + j\,\sigma_0\,f_0/f \quad (12)$$

where σ_1 and σ_0 are constants with respect to frequency, f_0 is a reference frequency. This has the same frequency dependence as the conductivity in the usual 2-fluid model for superconductors commonly used when analyzing YBCO films [5]:

$$\sigma_{super} = \sigma_n (T/T_c)^4 - j\,\frac{1-(T/T_c)^4}{\omega\,\mu\,\lambda_0^2} \qquad \textbf{(13)}$$

where σ_n is the normal conductivity, T is the absolute temperature, λ_0 is the penetration depth at T=0.

Because grain boundary impedance can have a significant effect [8],[5], we have not attempted to extract intrinsic material parameters from the estimated conductivity values. An example of the fit between the fitted model using PEM expressions and a YBCO filter is shown in Fig. 6. The designed response (calculated using the previous empirical model before the filter was made) is also shown; its near-prediction of the measured response shows that even approximate models can be sufficient for practical designs, and the superiority of more correct models difficult to judge from the data.

Fitting the PEM model to the data for the copper filter by adjusting the value for σ_{Cu} produced the estimates

$\sigma_{Cu} \approx 3.6\times10^7\ \Omega^{-1}m^{-1}$ at 297 K

$\sigma_{Cu} \approx 1.2\times10^8\ \Omega^{-1}m^{-1}$ at 77 K

Fitting the PEM model to the data for the best packaged YBCO filter by adjusting the values for σ_1 and σ_0 in (12) produced the estimate

$\sigma_{YBCO} \approx 5.6\times10^6 - j\ 6.2\times10^7\ (f_0/f)\ \Omega^{-1}m^{-1}$ at 77 K, where f_0 = 9 GHz

The characteristic surface impedance defined by (8) then gives

$Z_{s,Cu} \approx 0.031 + j\ 0.031\ \Omega$ at 9 GHz at 297 K

$Z_{s,Cu} \approx 0.017 + j\ 0.017\ \Omega$ at 9 GHz and at 77 K

$Z_{s,YBCO} \approx 0.002 + j\ 0.034\ \Omega$ at 9 GHz and at 77 K

For comparison, ideal room temperature copper with $\sigma=5.8\times10^7\ \Omega^{-1}m^{-1}$ has surface impedance $Z_s \approx 0.025 + j0.025$ Ω at 9 GHz. The quality factor formula [9]

$$Q = \frac{\pi}{\alpha\,\lambda_g} = \frac{8.686\,\pi}{\alpha_{dB}\,\lambda_g} \qquad \textbf{(14)}$$

where λ_g is the wavelength in the transmission line, with (7)-(11), gives the estimated values in Table 2.

The values for σ and Z_s found by the analysis above are an average over the area of the CPW lines, and approximate; actual conductivity probably varies for different sections of CPW. Also, other possible sources of loss have not been included, such as loss in input and output imperfections and bond wires. Dielectric losses are expected to be small for loss tangent 0.0001 or smaller using the usual formulas for CPW and microstrip [7] and were not included.

The PEM formulas can used for design as well as analysis, with the advantage of fewer adjustable parameters which must be determined than the empirical formulas used for the original filter design; only the complex conductivity is adjustable.

CONCLUSION

The design of coplanar waveguide filters using $YBa_2Cu_3O_7$ on $LaAlO_3$ has been described. Complete packaged CPW filters of YBCO have been made which exhibit losses superior to those of a corresponding copper filter throughout the 0 to 9.5 GHz passband. The PEM model [4] for films of thickness comparable to the skin depth or penetration depth can be used with commercial microwave CAD software and was employed to compare the surface impedance of the YBCO and copper filters. The model can be used for design. As more extensive data, verified closed form formulas for CPW, and improved films become available, future CPW components of YBCO should become standard elements in design and use.

ACKNOWLEDGMENTS

We thank J. Bautista for advice and providing a cryogenic refrigerator for microwave measurements and use of a wire-bonder, J. Bowen, D. Neff, G. Ortiz, and L. Duffy for advice, and S. Chavez, C. Cruzan, and J. Rice for assembly and wire-bonding expertise. This research, performed at the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, was sponsored by the National Aeronautics and Space Administration (NASA), Office of Aeronautics and Exploration Technology, by the Defense Advanced Research Projects Agency, and by the Strategic Defense Initiative Organization, Innovative Science and Technology Office.

REFERENCES

[1] A. A. Valenzuela, B. Daalmans, and B. Roas, "High-Q coplanar transmission line resonator of $YBa_2Cu_3O_{7-x}$ on $LaAlO_3$," Electron. Lett., vol. 25, 1989, pp. 1435-1436.

[2] W. Chew, L. J. Bajuk, T. W. Cooley, M. C. Foote, B. D. Hunt, D. L. Rascoe, and A. L. Riley, "High T_c superconductor coplanar waveguide filter," submitted to IEEE Electron Device Letters.

[3] S. Ramo, J. R. Whinnery, and T. Van Duzer, Fields and Waves in Communication Electronics. New York: John Wiley & Sons, 1965.

[4] H. Y. Lee and 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. 37, Dec. 1989, pp. 1904-1909.

[5] K. B. Bhasin, C. M. Chorey, J. D. Warner, R. R. Romanofsky, V. O. Heinen, K. S. Kong, H. Y. Lee, and T. Itoh, "Performance and modeling of superconducting ring resonators at millimeter-wave frequencies," 1990 IEEE MTT-S International Microwave Symposium Digest, May 1990, pp. 269-272.

[6] K.-S. Kong, C. W. Kuo, T. Kitazawa, and T. Itoh, "Analysis of the superconducting coplanar waveguide by combining spectral domain method and Phenomenological Equivalence Method," Electronics Letters, vol. 26, 13 Sept. 1990, pp. 1558-1560.

[7] K. C. Gupta, R. Garg, and I. J. Bahl, ch. 7 in Microstrip Lines and Slotlines. Dedham, MA: Artech House, 1979.

[8] T. L. Hylton, A. Kapitulnik, M. R. Beasley, J. P. Carini, L. Drabeck, and G. Grüner, Appl. Phys. Lett., vol. 53, 3 Oct. 1988, pp. 1343-1345.

[9] T. C. Edwards, Foundations for Microstrip Circuit Design. New York: John Wiley & Sons, 1981.

Table 1. Section dimensions of filter design. Ground plane separation is 0.250 mm.

Section	Length (mm)	Width (mm)	Characteristic Impedance (Ω)
1, 9	0.721	0.200	23
2, 8	0.997	0.010	78
3, 7	1.370	0.200	23
4, 6	0.761	0.010	78
5	1.918	0.200	23

Table 2. Estimated attenuation coefficients and Q values.

Width of center conductor of CPW	α_{dB} [dB/m] @ 9 GHz, 77 K		Q @ 9 GHz, 77 K	
	Cu	YBCO	Cu	YBCO
5-6 μm	90	20	30	100
46 μm	30	6	90	500
196 μm	50	5	60	600

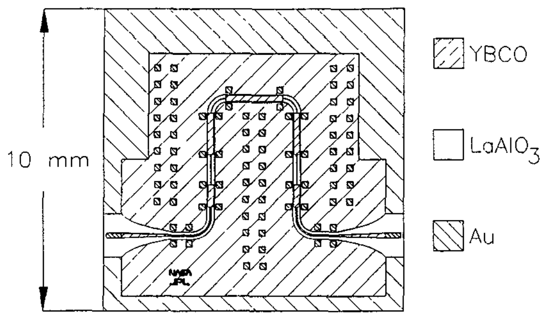

Fig. 1. Top surface of coplanar waveguide filter. Gold areas have YBCO underneath. Bond wires connect ground conductors at pads near discontinuities.

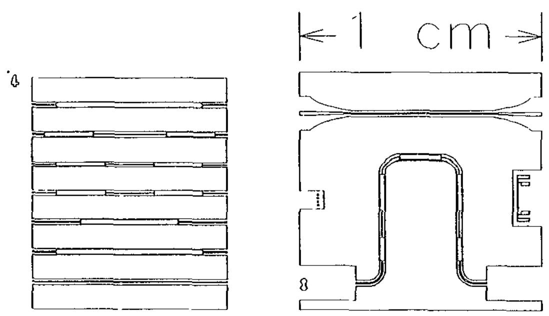

Fig. 2. CPW test structures for normal metal.

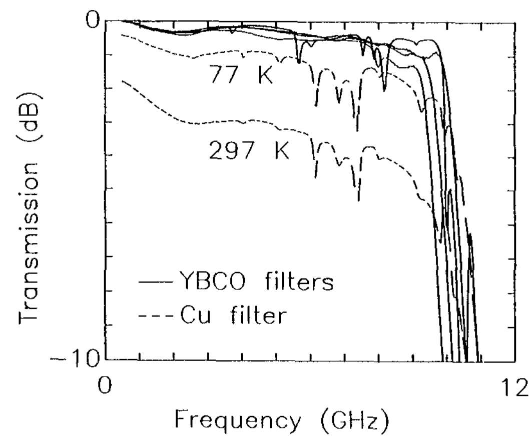

Fig. 3. Measured transmission of 4 YBCO filters and copper filter at 77 K, and copper filter at 297 K.

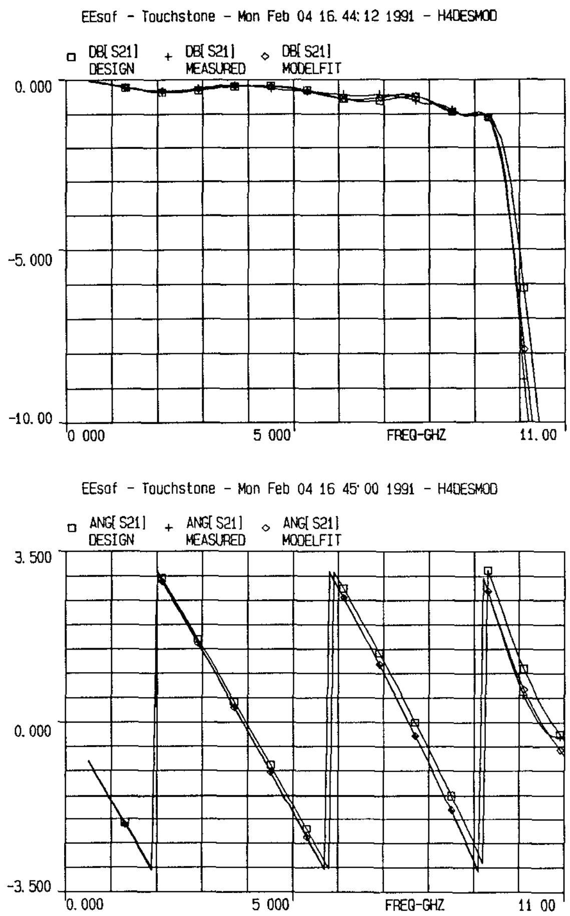

Fig. 4. Comparison of design using empirical model (DESIGN □), measured YBCO filter transmission (MEASURED +), and fit to data using PEM model (MODELFIT ◇) using Touchstone™. Vertical axis is $|S_{21}|$ in dB.