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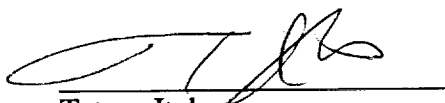
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
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CLEVELAND, OHIO 44135

ANALYSIS AND CHARACTERIZATIONS OF PLANAR TRANSMISSION  
STRUCTURES AND COMPONENTS FOR SUPERCONDUCTING AND  
MONOLITHIC INTEGRATED CIRCUITS

by

Tatsuo Itoh  
Department of Electrical and Computer Engineering  
The University of Texas  
Austin, Texas 78712

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Tatsuo Itoh

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## **ABSTRACT**

We have done the analysis and modelling of superconducting planar transmission lines. Theoretically, the highest possible Q values of superconducting microstrip line was calculated and, as a result, it provided the Q value that the experiment can aim for. As an effort to search for a proper superconducting transmission line structure, the superconducting microstrip line and coplanar waveguide have been compared in terms of loss characteristics and their design aspects. Also, the research has been expanded to a superconducting coplanar waveguide family in the microwave packaging environment. Theoretically, it was pointed out that the substrate loss is critical in the superconducting transmission line structures.

## **DESCRIPTION OF WORKS**

### **(1) Analysis of Microstrip Lines with Alternative Implementations of Conductors and Superconductors**

The motivation for this study was to provide the theoretical basis for the effective application of a superconductor to the microstrip line as well as other planar transmission lines. We have analyzed microstrip line structures in which either the strip or the ground plane or both are made of a high  $T_c$  superconductor. The effect of implementation of a superconductor to the strip and the ground plane has been studied with the calculation of a conductor loss of the structure by the Phenomenological Loss Equivalence Method (PEM). The theoretical values were compared with the experimental results from a ring resonator which is made of a gold ground plane and a high  $T_c$  superconductor,  $YBa_2Cu_3O_{7-x}$ , strip. Initially, the discrepancy between the theoretical and experimental results have been observed. This was due to incomplete characterization of a superconductor and poor quality of a superconducting film. Rather than using the measured surface resistance of a superconducting film and comparing theoretical and experimental values of the loss of the structure, we took an approach to characterize a superconducting film from the calculated and measured Q values of a ring resonator. The values of penetration depth and surface resistance obtained from this approach were reasonable. Also, Q values obtained from a superconducting film of the improved quality have been improved as theoretical values suggested.

### **(2) Design Aspects and Comparison Between High $T_c$ Superconducting Coplanar Waveguide and Microstrip Line**

The high  $T_c$  superconducting microstrip line and coplanar waveguide were compared in terms of the loss characteristics and the design aspects. The quality factor "Q" values for each structure were compared in respect to the same characteristic impedance with the comparable dimensions of the center conductor of the coplanar waveguide and the strip of the microstrip line. Also, the dielectric loss between the two structures were compared since the dielectric loss becomes a critical design aspect in the superconducting transmission line structures as the conductor loss is reduced. It is observed that the superconducting microstrip line has an advantage over the coplanar waveguide structure in terms of getting less conductor loss. However, the coplanar

waveguide provides the advantage over the microstrip line in the aspect of the design flexibility and the reduction of the substrate loss.

### **(3) Superconducting Conductor Backed Coplanar Waveguide.**

The coplanar waveguide appears to be a good structure for the application of a superconductivity because of its uniplanar nature. However, the conventional coplanar waveguide should be modified because it is not compatible with a cooling system. As a result, the conductor backed coplanar waveguide was proposed as a structure for the implementation of a superconductor in the coplanar waveguide. We calculated the conductor loss of a high  $T_C$  superconducting conductor backed coplanar waveguide. The inductance was calculated by the modified Spectral Domain Method(SDM). Then, the geometric factor was obtained by a numerical derivative of the inductance. This factor was used to calculate a conductor loss by the Phenomenological Equivalence Method(PEM). The conductor loss of the conductor backed coplanar waveguide was compared with the one of the conventional coplanar waveguide. It was observed that the conductor loss of the conductor backed coplanar waveguide is larger than the one of the conventional coplanar waveguide. This is due to the additional conductor loss from the backed ground plane of the conductor backed coplanar waveguide. However, the decrease is less than 15 %. Therefore, it is worth to implement a superconductor to the conductor backed coplanar waveguide. The design of the conductor backed coplanar waveguide resonator has been completed, and the experiment is on the progress.

### **PUBLICATIONS**

1. 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, Vol.I, pp. 269-272.(\* coauthors from NASA)
2. K. -S. Kong, H. -Y. Lee, T. Itoh, C. M. Chorey and K. B. Bhasin, "Analysis of Microstrip Lines with Alternative Implementations of Conductors and Superconductors", 1990 Asia-Pacific Microwave Conference, 1990.
3. K. -S. Kong, K. B. Bhasin and T. Itoh, "Design Aspects and Comparison between High  $T_C$  Superconducting Coplanar Waveguide and Microstrip Line", SPIE's International Symposium on Optical Engineering and Photonics in Aerospace Sensing, Orlando Florida, April 1-5, 1991. (to be published)

## **APPENDIX I**

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, Vol.I, pp. 269-272. (\* coauthors from NASA)

## **APPENDIX II**

K. -S. Kong, H. -Y. Lee, T. Itoh, C. M. Chorey and K. B. Bhasin, "Analysis of Microstrip Lines with Alternative Implementations of Conductors and Superconductors", 1990 Asia-Pacific Microwave Conference, 1990.

## **APPENDIX III**

K. -S. Kong, K. B. Bhasin and T. Itoh, "Design Aspects and Comparison between High  $T_c$  Superconducting Coplanar Waveguide and Microstrip Line", SPIE's International Symposium on Optical Engineering and Photonics in Aerospace Sensing, Orlando Florida, April 1-5, 1991. (to be published)

PERFORMANCE AND MODELING OF SUPERCONDUCTING RING RESONATORS AT  
MILLIMETER-WAVE FREQUENCIES.

K.B. Bhasin, C.M. Chorey\*, J.D. Warner, R.R. Romanofsky and V.O. Heinen

NASA Lewis Research Center  
21000 Brookpark Road  
Cleveland, OH 44135

\*Sverdrup Technology/LeRC Group  
2001 Aerospace Parkway  
Cleveland, OH 44142

K. S. Kong, H. Y. Lee and T. Itoh  
Department of Electrical and Computer Engineering  
The University of Texas at Austin  
Austin, TX 78712

**ABSTRACT**

Microstrip ring resonators operating at 35 GHz have been fabricated from laser ablated YBCO thin films deposited on lanthanum aluminate substrates. They were measured over a range of temperatures and their performance compared to identical resonators made of evaporated gold. Below 60° Kelvin the superconducting strip performed better than the gold, reaching an unloaded 'Q' ~1.5 times that of gold at 25° K. A shift in the resonant frequency follows the form predicted by the London equations. The Phenomenological Loss Equivalence Method is applied to the ring resonator and the theoretically calculated Q values are compared to the experimental results.

**INTRODUCTION**

Recent observations of low surface resistance at microwave and millimeter wave frequencies in thin superconducting films [1] suggest their use for low loss/high Q microstrip circuits. Of interest is the surface resistance exhibited by these films across a wide frequency range. To date, measurements of surface resistance in the Ka band and above have been by the cavity technique. This technique fails to model microstrip losses completely because it neglects substrate losses and fails to adequately probe the film-substrate interface. Microstrip resonators patterned from thin films on microwave substrates allow direct measurement of microstrip losses. Several groups have made such measurements at lower microwave frequencies. [2,3,4] In this paper we report on the direct measurement of losses by Ka band microstrip resonators made from laser ablated YBCO films on lanthanum aluminate. Also, we calculate the Q values of the structure using the Phenomenological Loss Equivalence Method and invoking superposition of the internal impedances of the strip and ground plane of the microstrip

line. The calculated Q value of the ring resonator with a superconducting strip and a normal conducting ground plane is compared with the experimental results.

**GROWTH AND PATTERNING**

The superconducting films were deposited by laser ablation of a sintered YBCO pellet onto a heated (700°C) lanthanum aluminate substrate in a 100 mtorr oxygen atmosphere and then slowly cooled to room temperature in 1 atmosphere of oxygen. [5] Films with very smooth surfaces and Tc's of 89.8 have been produced; X-ray analysis has shown that they are c-axis aligned. The microstrip resonators were patterned by standard photolithography using negative photoresist and a 'wet' chemical etchant. This etchant was either a 3% solution of bromine in ethanol or dilute phosphoric acid in water. A metal ground plane was deposited by first evaporating 100 Å of Ti for adhesion followed by 1 micron of gold. In addition to the resonator, each chip also had a test bar for direct Tc testing of the patterned film. Identical resonators were fabricated entirely from gold (both strip and ground plane) using evaporation and lift-off to define the strip.

The resonators were measured using a Hewlett-Packard 8510 Network Analyzer, operating in WR-28 waveguide. The microstrip circuit was mounted in a tapered ridge waveguide to microstrip test fixture which was mounted at the second stage of a two stage, closed cycle helium refrigerator. Circuit temperatures reached approximately 20°K and were monitored by a silicon diode sensor mounted in the test fixture. The entire cold finger and test fixture were enclosed in a custom designed vacuum can. Microwave coupling to the test fixture was through 6 inch sections of WR-28 waveguide made of thin wall stainless steel to minimize heat conduction. Vacuum was maintained at the waveguide feedthroughs by means of 'O' rings and mica sealing windows.

### THEORETICAL CALCULATION OF Q

The theoretical Q values were calculated using the Phenomenological Loss Equivalence Method (PEM). [6] This method is applicable to cases where the strip conductor thickness is on the order of a skin depth (for a normal metal) or a penetration depth (for a superconductor). The Incremental Inductance Rule, which is often used to calculate microstrip losses, can only be applied in the case of shallow field penetration, which is not satisfied in this study. Also, PEM has the advantage of simple calculation compared with other numerical techniques such as the Finite Element Method. The technique proceeds on the basis of separately calculating the internal impedances of the strip and the ground plane through use of an equivalent isolated strip, and then adding these impedances to the external impedance of the microstrip structure. First, the ground plane is assumed to be a perfect conductor so that there is no magnetic field penetration into it as shown in figure 1. A geometric factor (G1) for the strip line is then obtained from the magnetic field penetration into it. This G1 factor is used to obtain an equivalent strip; from which the internal impedance of the microstrip line under the assumption of perfect ground plane can be obtained as

$$Z_{i1} = G_1 \cdot Z_{s1} \cdot \coth(Z_{s1} \cdot \sigma_1 \cdot A \cdot G_1)$$

where  $Z_{s1}$ ,  $\sigma_1$  and A are the surface impedance, the conductivity of the material and the cross sectional area of the strip, respectively. Next we consider the strip as a perfect conductor as shown in figure 1. Then a geometric factor (G2) is obtained for the field penetration into the ground plane. With the value G2, we obtain the internal impedance of the ground plane based on the assumption of a perfect strip,

$$Z_{i2} = G_2 \cdot Z_{s2} \cdot \coth(Z_{s2} \cdot \sigma_2 \cdot A \cdot G_2)$$

where  $Z_{s2}$  and  $\sigma_2$  are surface impedance and conductivity of the ground, respectively. The internal impedance of the microstrip line is obtained by adding  $Z_{i1}$  and  $Z_{i2}$ . We add this internal impedance to the external inductance and calculate the propagation constant of the microstrip line by using a transmission line model. It should be emphasized that (1) and (2) are applicable to any field penetration depth.

The conductor losses of the structure in fig. 2 were calculated by applying the method explained above. Then, the Q values of each resonator were calculated by additional consideration of substrate loss; radiation loss was assumed negligible. For the calculation, the value of  $5.8 \times 10^{-4}$  was used for the loss tangent. Since the current is more concentrated on the strip, the implementation of a superconductor in the strip has more influence on the loss.

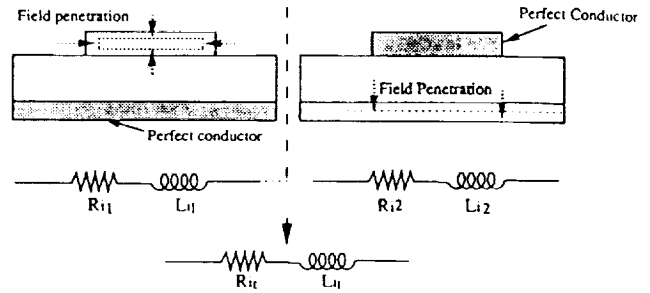


Figure 1. Field penetration in the strip and ground plane; for PEM calculation.

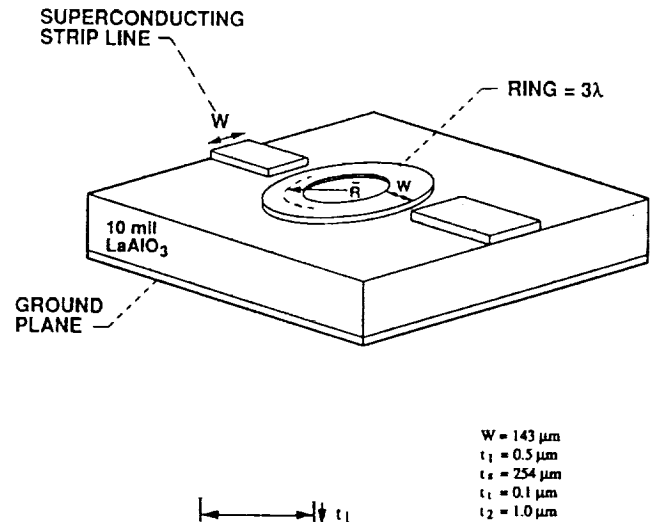


Figure 2. 35GHz Ring Resonator Structure.

The extent of the effect of implementing a superconductor in the microstrip line can be different for different geometries.

### RESULTS AND DISCUSSION

In figure 3 are shown plots of S11 for a superconducting resonator at several temperatures. This plot is of the reflected power from the resonator in the test fixture and is thus a measure of the loaded 'Q'. Two features are apparent; 1) the coupling changes with temperature (in this case, starting at near critical coupling just below Tc and going to overcoupled at lower temperatures), and 2) the resonant frequency shifts with temperature. The change in the resonant frequency vs temperature is plotted in figure 4 along with the resonant frequencies of a gold resonator. The variation observed in the gold resonator follows the form expected from thermal contraction in the substrate. But since accurate data on lanthanum aluminate is not readily available, precise comparisons are not possible. The variation seen in the superconducting resonator is a consequence of the dependence of the internal impedance of the strip on the changing normal/superconducting electron densities. The internal inductance of a superconducting strip over a ground plane is given by:[7]

$$L_{int} = \mu_0 \cdot \lambda \cdot \coth(t/\lambda)$$

Assuming the Gorter-Casimir temperature dependence of  $\lambda$ :

$$\lambda(T) = \frac{\lambda_0}{[1 - (T/T_c)^4]^2}$$

the form of the resonant frequency variation based on the changing line inductance matches the experimental observations. However, attempts at numerical fitting to extract  $\lambda_0$ , result in  $\lambda_0$  in excess of 1 micron, indicating that the film quality may not be at its highest.

The best circuit to date has been from a 6500 Å film with a post-processing Tc of 79°K. The unloaded Q of this circuit is plotted against temperature in figure 5 along with the unloaded Q of an identical gold resonator. The Q of the superconducting circuit rises sharply below Tc, exceeding the Q of the gold circuit at ~60°K and reaching a value of 1.5 times that of the gold resonator at 25°K. Comparing the experimental results with the calculated values in the same figure, we see that for the gold resonator, the PEM calculation matches the experimental fairly well. The measured superconducting 'Q', however, is much lower than the calculated values. Several reasons can be given for this. First, the values for the complex conductivity of the superconductor used in the PEM calculation were obtained by microwave reflectance/transmission measurements on separate laser ablated films.[8] It is likely that the quality of those films was higher than the resonator film, in part because these films were

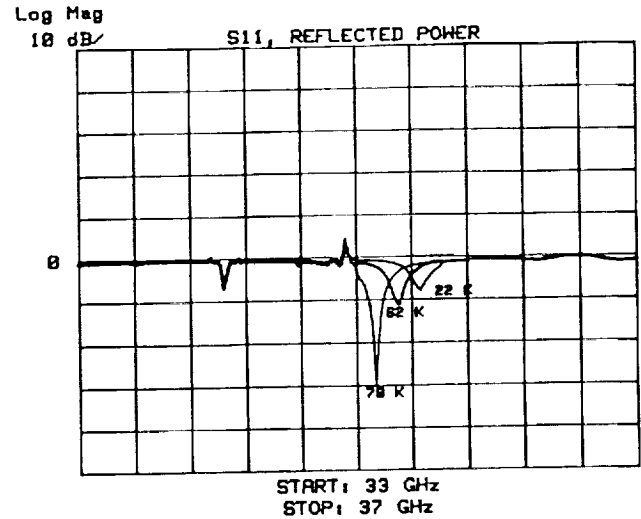


Figure 3. S11 of the superconducting resonator in its test fixture, at three temperatures.

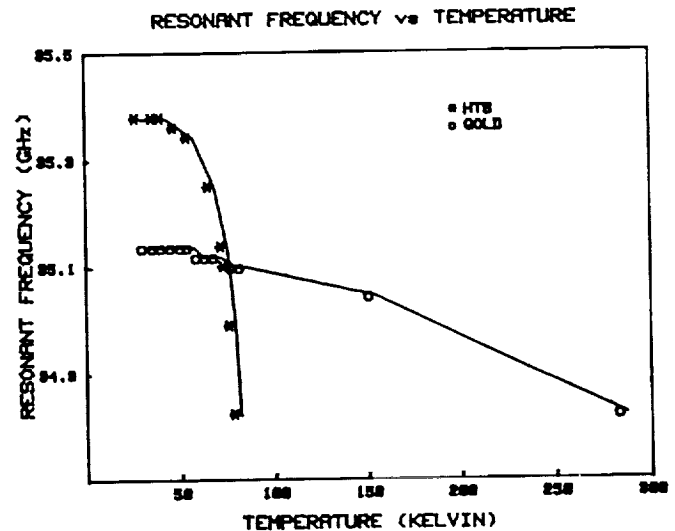


Figure 4. Resonant frequency vs temperature for superconducting and normal strips.

unpatterned. In addition, substrate losses in the PEM were calculated on the basis of  $\tan\delta=5.8 \times 10^{-4}$  but accurate values for lanthanum aluminate are not available so the actual value may be higher or lower. It seems likely that improvements in the measured Q are possible with increased film quality.

### CONCLUSIONS

Ring resonator circuits were fabricated from laser ablated YBCO superconducting films on lanthanum aluminate to determine transmission line losses at millimeter wave frequencies. At 25°K the unloaded Q of the superconducting resonator was 1.5 times the Q of identical resonators made of gold. A shift in the resonant frequency with temperature follows the form predicted by the London equation. Using the PEM we calculated the Q values of the ring resonator with a thin YBCO strip and a gold ground plane. The theoretical results were compared with experimental results of the ring resonator of that structure. The calculated results predict higher values of Q than those actually observed, but improved film quality should increase measured Q values.

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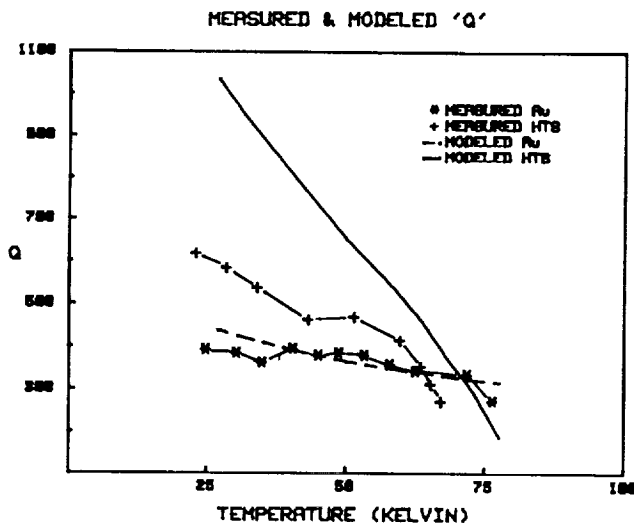


Figure 5. Measured and calculated values of unloaded Q for superconducting and normal resonators.

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## Analysis of Microstrip Lines with Alternative Implementations of Conductors and Superconductors

*K.-S. Kong\*, H.-Y. Lee\*, T. Itoh\*, C. M. Chorey\*\* and K.B. Bhasin\*\**

*\*Department of Electrical and Computer Engineering  
The University of Texas at Austin, Austin, TX 78712  
U.S.A.*

*\*\*NASA Lewis Research Center  
Cleveland, Ohio 44135  
U.S.A.*

### Abstract

This paper presents analysis of microstrip line structures in which either the strip or the ground plane or both are made of a high  $T_c$  superconductor. The effect of implementation of a superconductor to the strip and the ground plane is explained with the calculation of a conductor loss of the structure by the Phenomenological Loss Equivalence Method (PEM). The theoretical values are compared with the experimental results from a ring resonator which is made of a gold ground plane and a high  $T_c$  superconductor,  $YBa_2Cu_3O_{7-x}$ , strip.

### Introduction

In this paper, we calculate and compare  $Q$  values of the microstrip line structures in which either the strip or the ground plane or both are a high  $T_c$  superconductor. The motivation for this study is to provide the theoretical basis for the effective application of a superconductor to the microstrip line as well as other planar transmission lines. The analytical method in this paper is based on the Phenomenological Loss Equivalence Method (PEM) [1,2] and the introduction of the superposition principle of the internal impedances from the strip and the ground plane of the microstrip line. By using this method, we calculate the  $Q$  value of the ring resonator which has a superconducting strip and a normal conducting ground and compare the results with the experimental data.

### Analysis of Various Superconducting Microstrip Line Structure

We analyze the various superconducting microstrip line structures that have alternative implementations of a superconductor and a normal conductor into the strip or the ground plane as shown in Fig.1. There are field penetrations even inside of the superconductor. These field penetrations contribute to the internal impedance and cause the conductor loss in the microstrip line structure as shown in Fig.2. The internal impedances from strip conductor and the ground plane are separately calculated by PEM. Then, the total internal impedance is obtained by using the superposition of internal impedances. The internal impedance of each case is obtained by considering the cases where either strip or the ground plane is perfect.

When the ground plane is assumed to be perfect, the field penetration occurs only in the strip conductor. In this case, the geometric factor, say  $G_1$ , of the microstrip line is obtained from the magnetic field penetration inside of the strip conductor. The equivalent strip [1,2] is obtained from  $G_1$ . The internal impedance of microstrip line under the assumption of a perfect ground plane can be obtained as  $Z_{i1} = G_1 \cdot Z_{s1} \cdot \coth(Z_{s1} \cdot \sigma_1 \cdot A \cdot G_1)$  where  $Z_{s1}$ ,  $\sigma_1$  and  $A$  are the surface impedance, the conductivity of the material and the cross section ( $w \cdot t$ ) of the strip, respectively. Next, we consider the case where the field penetration occurs only in the ground plane. In this case, the geometric factor,  $G_2$ , is obtained from the field penetration in the ground plane. The internal impedance from the ground plane is obtained as  $Z_{i2} = G_2 \cdot Z_{s2} \cdot \coth(Z_{s2} \cdot \sigma_2 \cdot A \cdot G_2)$  where  $Z_{s2}$  and  $\sigma_2$  are surface impedance and conductivity of the ground, respectively. Then, the total internal impedance is obtained by adding  $Z_{i1}$  and  $Z_{i2}$ . We calculate the propagation constant of the microstrip line structure by adding this internal impedance to the external impedance and by using the transmission line model. Since our method is based on the PEM, this can be applied to any field penetration depth compared with the conductor thickness as demonstrated in reference [1, 2].

### Comparison Between Microstrip Lines with Various Superconductor Implementation

The conductor losses of each microstrip line in Fig.1 are calculated by applying the method explained above. Then, we calculate  $Q$  values of each strip line

by additional consideration of substrate loss [3]. This will give us insight to the effects of an application of superconductor on microstrip line. The dimensions of the structure are shown in Fig.3 (a). For the calculation, we use the measured conductivity values of the  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  film obtained from the power transmitted through the film and a two fluid model [4]. The calculated Q values of each structure at 35 GHz are shown and compared in Fig.3. In this calculation, the value of  $5.8 \times 10^{-4}$  is used for loss tangent. Since the current is more concentrated on the strip, the implementation of a superconductor in the strip gives more influence on the loss as expected. The extent of an effect of the implementation of a superconductor in the microstrip line can be different for different geometric structures of the microstrip line.

Next, we compare our calculated results with the experimental results from the ring resonator structure shown in Fig.4. This ring resonator has the resonant frequency of 35.0 GHz. The details of the fabrication of this structure and the measurements are presented elsewhere [5]. The strip of this ring resonator is a thin film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  deposited on  $\text{LaAlO}_3$  by a laser ablated technique. The ground plane consists of Ti / Au. A thin Ti layer is employed to make the deposition of the gold on the substrate and its effect on the structure is negligible because it is thin compared with a gold layer. Fig.5 shows the experimental Q values and the calculated Q values with the variation of loss tangent of the substrate. The calculated values of Q are higher than the experimental results. There are several factors for this discrepancy between the experimental and theoretical results. The ring resonator was built with a  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  film different from the film on which the conductivity values were measured. The  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  film used in the ring resonator has lower  $T_c$  and lower quality than the one used in the conductivity measurement. Also, it is more affected by the surface roughness because it is patterned. Another factor can be the edge current effect on the superconducting ring resonator. Also, since the conductor loss from the gold and superconductor decreases at the low temperature region, the substrate loss becomes more dominant. However, the information on the loss tangent of the substrate is not available at low temperature region. As we can observe in Fig.5, the Q values depend on the value of loss tangent of the substrate used in the calculation. The accurate characteristics of the substrate should be done in order to make it meaningful to compare the theoretical and experimental results.

### Conclusion

In this paper, we presented a theoretical analysis of the superconducting microstrip lines with the various implementations of a superconductor and a normal conductor into the strip or the ground plane of the microstrip line. By using the method presented, we calculated the Q values of a ring resonator with the thin  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  strip and the gold ground plane. This theoretical results are compared and discussed with

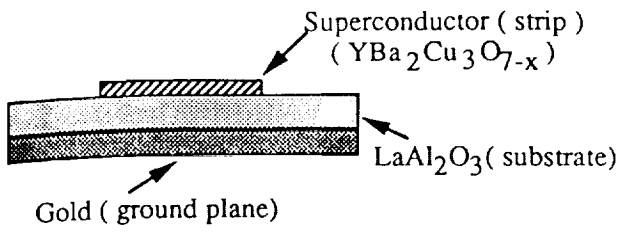
experimental results of a ring resonator with the thin  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  strip and the gold ground plane. It was found that the substrate loss becomes very critical at the superconducting microstrip line.

### Acknowledgement

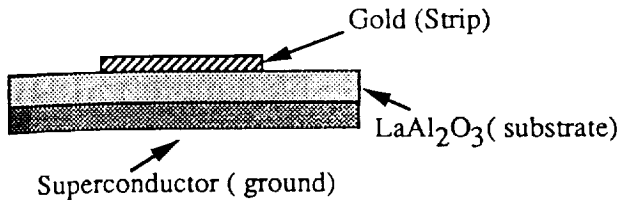
The authors at the University of Texas were supported by the cooperative agreement NCC-3154 from NASA and the Texas Advanced Technology Program. The PEM method was originally developed under support by grant N00014-89-J-1006 at The University of Texas at Austin from the U.S. Office of Naval Research.

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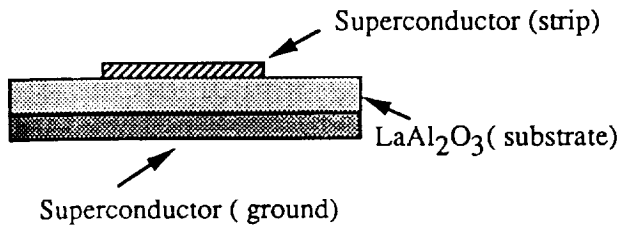
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(a)



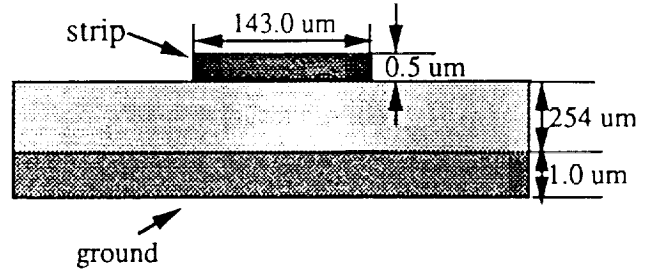
(b)



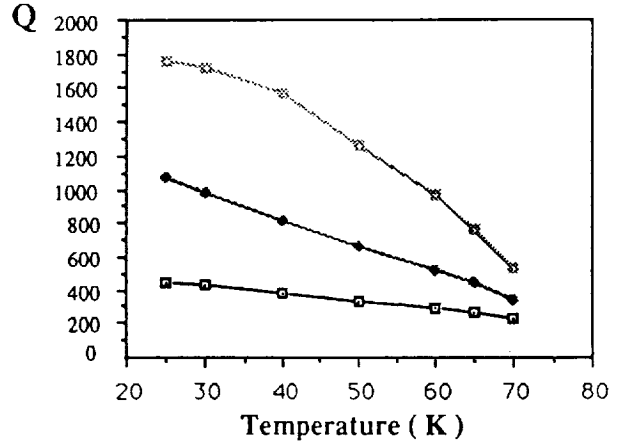
(c)

- (a) superconducting strip, normal conducting ground  
 (b) superconducting ground, normal conducting strip  
 (c) superconducting strip, superconducting ground

Fig. 1 Superconducting Microstrip Lines



(a) Microstrip line



- case 1
- ◆- case 2
- \* case 3

- case 1 ) strip : gold                      ground : superconductor  
 case 2 ) strip : superconductor      ground : gold  
 case 3 ) strip : superconductor      ground : superconductor

(b) Q-values of superconducting microstrip lines

Fig.3 Dimensions and Q-values of Superconducting Strip Lines.

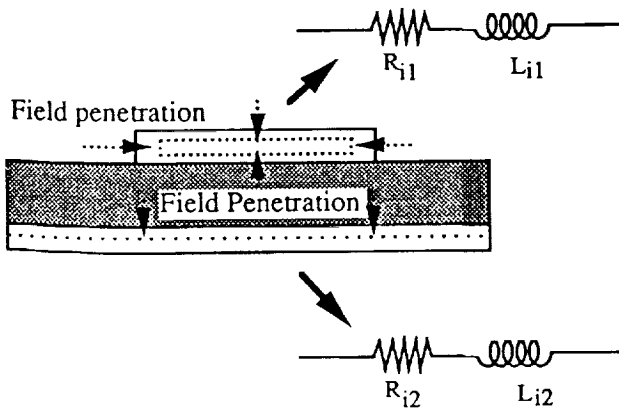


Fig.2 Field penetration in the strip and the ground plane.

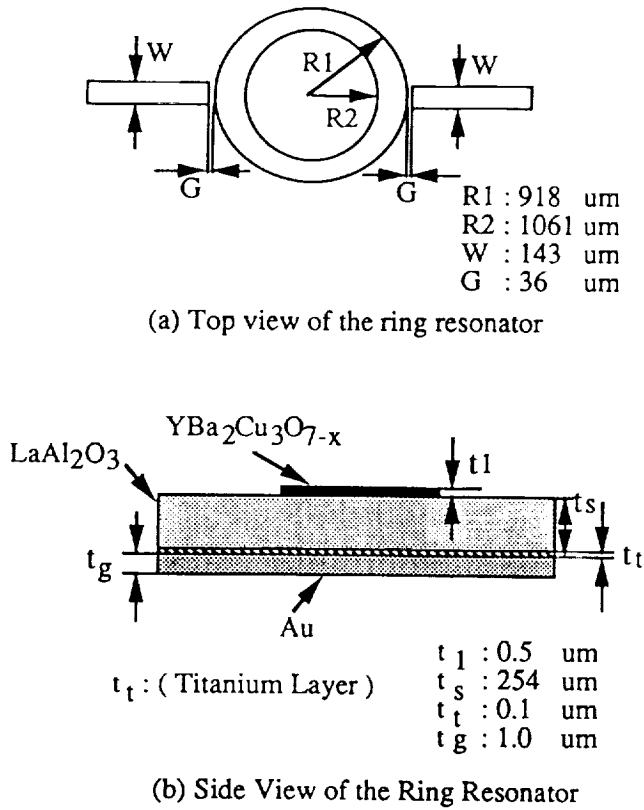


Fig. 4 Superconducting Ring Resonator.

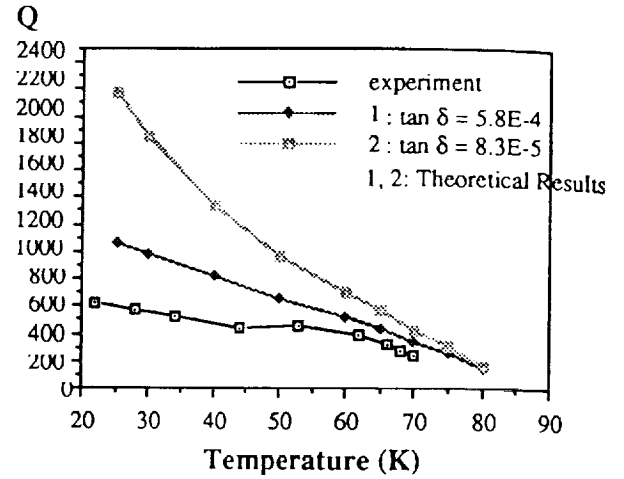


Fig. 5 Experimental and Theoretical Values of Q in Superconducting Ring Resonator

## Design Aspects and Comparison Between High $T_c$ Superconducting Coplanar Waveguide and Microstrip Line

K. S. Kong\*, K. B. Bhasin\*\* and T. Itoh\*\*\*

\*Department of Electrical and Computer Engineering  
The University of Texas at Austin  
Austin, Texas 78712

\*\*NASA Lewis Research Center  
Cleveland, Ohio 44135

\*\*\*Department of Electrical Engineering  
The University of California, Los Angeles  
Los Angeles, CA 90024

### ABSTRACT

The high  $T_c$  superconducting microstrip line and coplanar waveguide are compared in terms of the loss characteristics and the design aspects. The quality factor "Q" values for each structure are compared in respect to the same characteristic impedance with the comparable dimensions of the center conductor of the coplanar waveguide and the strip of the microstrip line. Also, the advantages and disadvantages for each structure are discussed in respect to passive microwave circuit applications.

### 2. INTRODUCTION

There has been a significant effort to develop high  $T_c$  superconducting film on various substrates for low loss microwave circuit applications[1,2]. Resonator circuits based on transmission line structures, such as microstrip line and coplanar waveguide, have been used to obtain losses in superconducting films. Models have also been developed to calculate losses in these films and in some cases comparison made to experimental results[3,4]. Presently, microstrip line is more widely used because there are more design information available about the structure as compared to coplanar waveguide structure. However, it is expected that the coplanar waveguide should get more attention because it needs only one sided film as opposed to microstrip line which requires double sided film.

In this paper, we compare the two superconducting transmission line structures in respect to their application to passive microwave circuits. The loss characteristics of the two structures are compared and discussed. In order to achieve this goal, we calculate the conductor losses of the high  $T_c$  superconducting coplanar waveguide and microstrip line by Phenomenological Equivalence Method[5,6]. Also, the dielectric loss between the two structures is compared since the dielectric loss becomes a critical design aspect in the superconducting transmission line structures as the conductor loss is reduced. In conclusion, we also discuss their advantages and disadvantages.

### 3. CALCULATION OF THE CONDUCTOR LOSS

The phenomenological loss equivalence method[7] is used to calculate the conductor loss of the microstrip line and the coplanar waveguide. In this paper, only key steps will be explained. The main idea of this method is to transform the transmission line into the single equivalent strip which has the same conductor loss as the original transmission line structure. For each structure, the single equivalent strip is obtained by considering the field penetration into the conductors[5,6]. The width of the equivalent strip is expressed in term of G factor.

$$W_e = \frac{1.0}{G} \quad (1)$$

Then, the thickness of the equivalent strip is obtained

$$t_e = AG \quad (\text{Microstrip line: } A = W \times t, \text{ Coplanar waveguide: } A = S \times t) \quad (2)$$

The internal impedances of the microstrip line and the coplanar waveguide are expressed as

$$Z_i = G Z_s \coth(Z_s \sigma_{sc} AG). \quad (3)$$

where  $Z_s$  and  $\sigma_{sc}$  are the surface impedance and the conductivity value of the superconductor. The surface impedance ( $Z_s$ ) of the superconductor is expressed as

$$Z_s = \sqrt{\frac{j\omega\mu_0}{\sigma_{sc}}} \quad (4)$$

with the two-fluid model for the conductivity  $\sigma_{sc}$ . Then, the propagation constants ( $\gamma$ ) of the structures are calculated by using the transmission line model by adding the internal impedance to the external inductance and the capacitance.

$$\gamma \text{ (propagation constant) } = \alpha \text{ (attenuation constant) } + j\beta \text{ (phase constant)} \quad (5)$$

Then, the quality factor "Q" value of the resonator is calculated as

$$Q \text{ (Quality Factor) } = \frac{\beta}{2\alpha} \quad (6)$$

#### 4. COMPARISON OF SUPERCONDUCTING MICROSTRIP LINE AND COPLANAR WAVEGUIDE STRUCTURES

In this section, the characteristics of the superconducting microstrip line and coplanar waveguide are compared in respect to the conductor loss, substrate loss and the flexibility of a design. Fig.1 shows the configurations of the microstrip line and the coplanar waveguide, and the parameters of a superconductor. The comparison of the microstrip line and the coplanar waveguide in respect to loss characterization should be done carefully since two structures have different configurations. The difficulty comes from the fact that the conductor loss depends on not only the configuration but also the size of the transmission line structure. Therefore, the dimensions of each structure in comparison should be carefully selected with a certain design criteria for the meaningful comparison.

First, we compare the conductor losses in the microstrip line and coplanar waveguide which have same characteristic impedance with comparable dimensions of the center conductor of the coplanar waveguide and the strip of the microstrip line. Fig.2 shows Q values of two structures with the variation of the frequency and the temperature. It is observed that Q values of the microstrip line are about 6.6 % higher than those of the coplanar waveguide with the given dimensions in Fig. 2.

Next, we investigate the effect of size of structures on the comparison of Q values between two structures. We compare three sets of the microstrip line and the coplanar waveguide as shown in Fig.3, where the characteristic impedance of all structures is same. In each set, dimensions of the center conductor of coplanar waveguide and the strip of the microstrip line are comparable. It is observed that differences of Q values between the microstrip line and the coplanar waveguide increase with the increased

width of conductors and thickness of the substrate. Therefore, the use of a superconducting microstrip line will be more effective compared with the coplanar waveguide in terms of getting high Q as the size of the resonator becomes larger.

Now, we consider the variation of the Q values with the change of the characteristic impedance. Fig. 4 shows the comparison of the Q values between two structures with variations of characteristic impedance with a fixed substrate thickness of 254.0  $\mu\text{m}$ . It is observed that the differences of the Q values between two structures decrease as the characteristic impedances of the lines increase.

As observed above, the microstrip line has higher Q values than those of the coplanar waveguide when the sizes of the conductors in each structure are comparable. Therefore, the microstrip line has an advantage in obtaining low conductor loss. However, the comparison can be carried out from the aspect of the design flexibility. When the thickness of the substrate and the characteristic impedance are given in the microwave circuit, there is only one design parameter (width of the strip) in the microstrip line while the coplanar waveguide has two parameters (the gap and the width of the center conductor). For example, with design conditions of substrate thickness of 127  $\mu\text{m}$  and the characteristic impedance of 45, the microstrip line and the coplanar waveguide can be designed with parameters shown in Fig.5. In this case, the higher Q value can be obtained from the coplanar waveguide as shown in Fig. 5. Therefore, under a certain design condition, the higher Q value can be obtained by using the coplanar waveguide.

There are other aspects to consider in the application of a superconductor to transmission lines. First, the substrate loss should be considered. In superconducting transmission lines, the substrate loss becomes an important factor since the conductor loss is reduced. There have been several reported values of loss tangent of  $\text{LaAlO}_3$ [8,9]. However, the lack of consistency of the loss tangent values in these publications indicates the difficulty of a characterization of the substrate material for a superconducting film at the low temperature. The calculation of the substrate loss is based on the simple expression[10] and Loss tangent value of  $8.3 \times 10^{-5}$  is selected for the substrate loss. Fig. 6 shows the substrate losses of the microstrip line and coplanar waveguide with the given dimensions. It is observed that the substrate loss in the microstrip line is higher than the one in the coplanar waveguide. Therefore, the dielectric loss becomes more critical in the design of superconducting microstrip line compared with the coplanar waveguide. The other consideration to make is a possible degradation effect due to the high current distribution at the edges of the conductors. The coplanar waveguide has more conductor edges, where there are high current distributions, as shown in the Fig.7, compared with the microstrip line. As pointed out in [11], the conductivity of the superconductor varies with the power level. As a result, the CPW may be more affected by the degradation of the conductivity of a superconductor.

## 5. CONCLUSION

The comparison between the superconducting coplanar waveguide and microstrip line was presented. The superconducting microstrip line has an advantage over the coplanar waveguide structure in terms of getting less conductor loss. However, the coplanar waveguide provides the advantage over the microstrip line in the aspect of the design flexibility and the reduction of the substrate loss.

## 6. ACKNOWLEDGMENTS

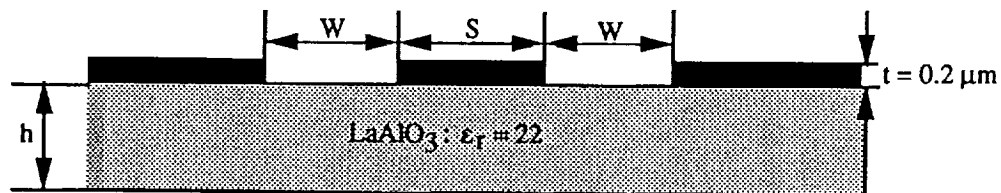
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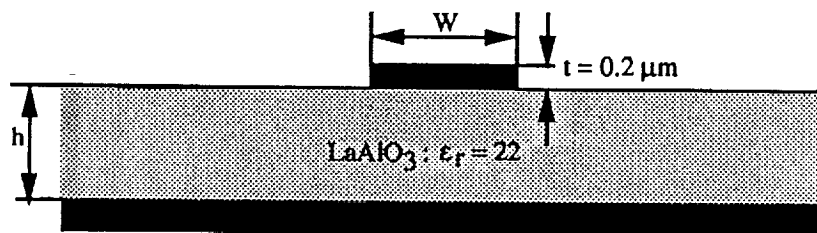
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Parameters of a superconductor:  $T_c = 92.5 \text{ K}$ ,  $\lambda_0 = 0.2 \mu\text{m}$ ,  $\sigma_n = 1.0 \text{ S}/\mu\text{m}$



(a) Microstrip Line.



(b) Coplanar Waveguide.

Fig. 1. Configuration of superconducting microstrip line and coplanar waveguide.



—□— Microstrip Line:  $w = 48 \mu\text{m}$ ,  $h = 127 \mu\text{m}$ ,  $Z_0 = 50.05$   
 —◆— Coplanar Waveguide:  $w = 80 \mu\text{m}$ ,  $s = 50 \mu\text{m}$ ,  $h = 127 \mu\text{m}$ ,  $Z_0 = 50.66$

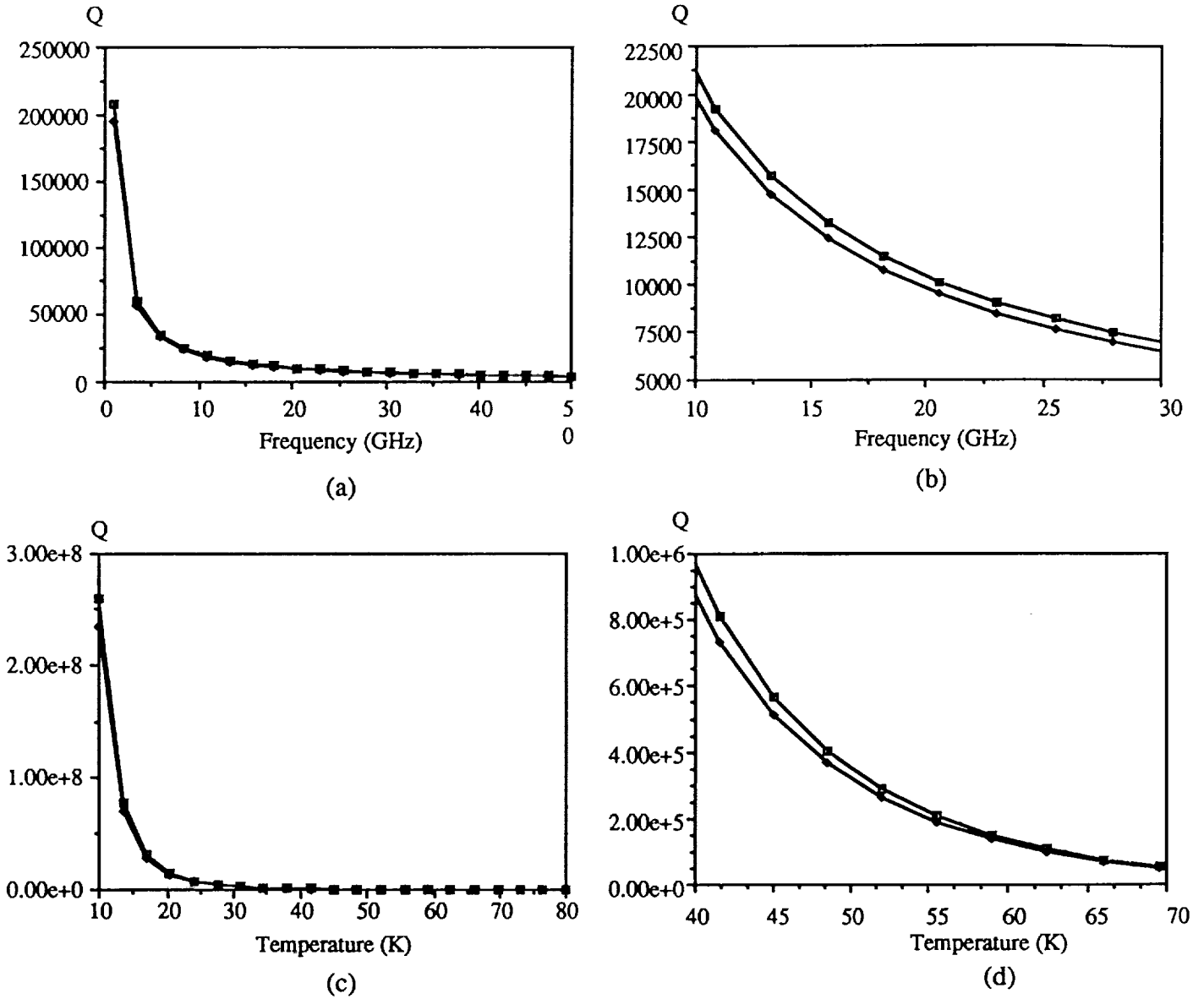
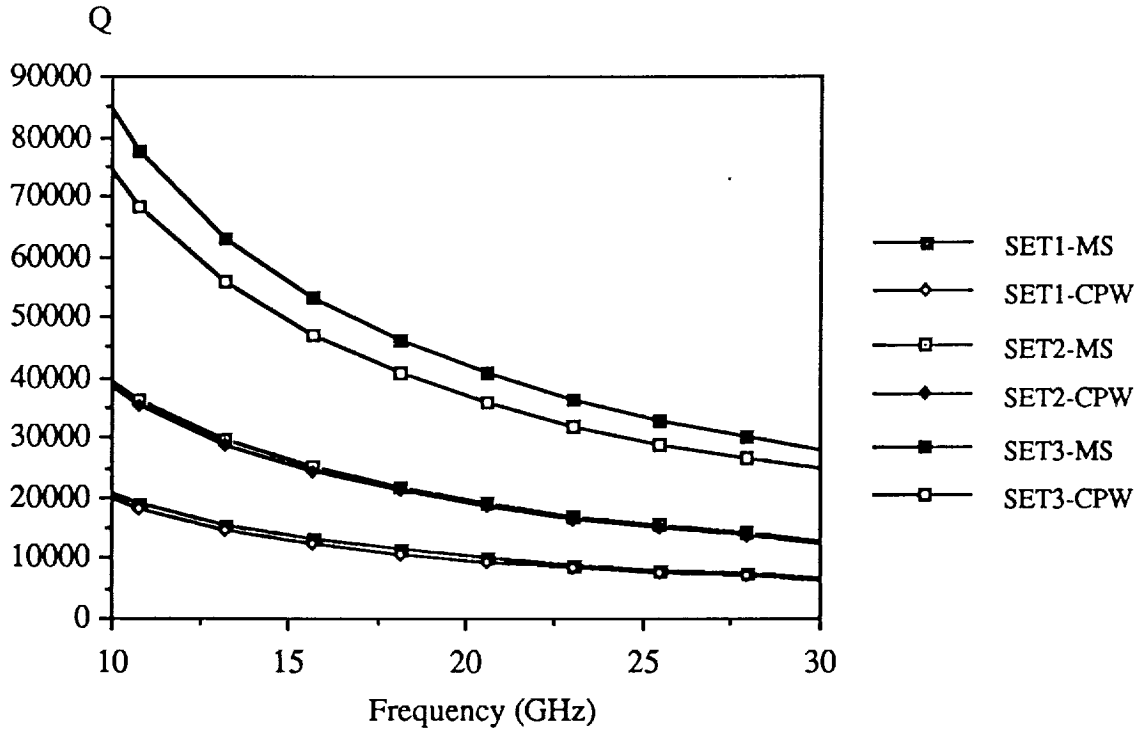


Fig. 2. Q values of the microstrip line and the coplanar waveguide.  
 ( Parameters of the material are shown in Fig. 1 )  
 (a) Q with the variation of the frequency.  
 (b) Magnified view of (a) in the frequency region from 10 to 30 GHz.  
 (c) Q with the variation of the temperature.  
 (d) Magnified view of (c) in the temperature region from 40 to 70 K.



Set 1: Microstrip Line:  $w = 48 \mu\text{m}$ ,  $h = 127 \mu\text{m}$ ,  $Z_0 = 50$

Coplanar Waveguide:  $w = 80 \mu\text{m}$ ,  $s = 50 \mu\text{m}$ ,  $h = 127 \mu\text{m}$ ,  $Z_0 = 50$

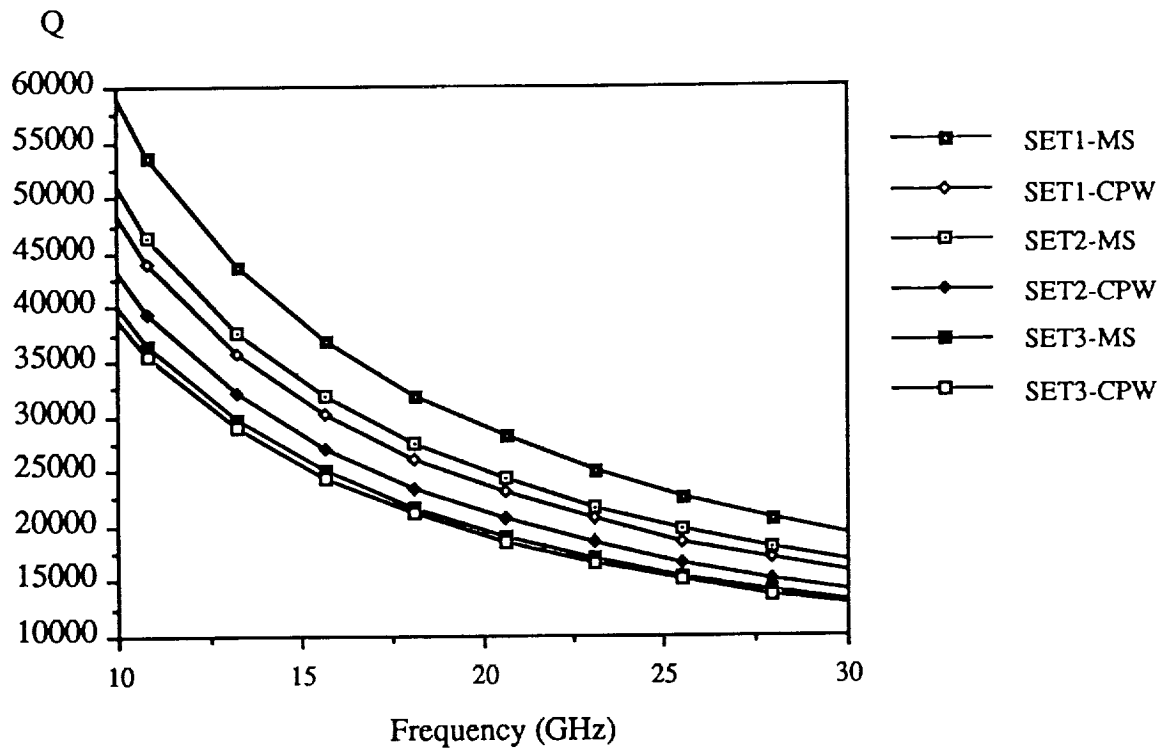
Set 2: Microstrip Line:  $w = 90 \mu\text{m}$ ,  $h = 254 \mu\text{m}$ ,  $Z_0 = 50$

Coplanar Waveguide:  $w = 160 \mu\text{m}$ ,  $s = 100 \mu\text{m}$ ,  $h = 254 \mu\text{m}$ ,  $Z_0 = 50$

Set 3: Microstrip Line:  $w = 200 \mu\text{m}$ ,  $h = 508 \mu\text{m}$ ,  $Z_0 = 50$

Coplanar Waveguide:  $w = 300 \mu\text{m}$ ,  $s = 200 \mu\text{m}$ ,  $h = 508 \mu\text{m}$ ,  $Z_0 = 50$

Fig.3 Comparison of Q values from Microstrip line and Coplanar Waveguide with varied sizes of the structures with the characteristic impedance of 50 ohm.



Set 1 ( $Z_0=40$  ohm): Microstrip Line:  $w = 165 \mu\text{m}$ ,  $h = 254 \mu\text{m}$   
 Coplanar Waveguide:  $w = 118 \mu\text{m}$ ,  $s = 165 \mu\text{m}$ ,  $h = 254 \mu\text{m}$

Set 2 ( $Z_0=45$  ohm): Microstrip Line:  $w = 130 \mu\text{m}$ ,  $h = 254 \mu\text{m}$   
 Coplanar Waveguide:  $w = 130 \mu\text{m}$ ,  $s = 130 \mu\text{m}$ ,  $h = 254 \mu\text{m}$

Set 3 ( $Z_0=50$  ohm): Microstrip Line:  $w = 90 \mu\text{m}$ ,  $h = 254 \mu\text{m}$   
 Coplanar Waveguide:  $w = 160 \mu\text{m}$ ,  $s = 100 \mu\text{m}$ ,  $h = 254 \mu\text{m}$

Fig.4 Comparison of Q values from the microstrip line and coplanar waveguide with the variation of the frequency.

—□— Microstrip line :  $w = 60.0 \mu\text{m}$ ,  $h = 127.0 \mu\text{m}$ ,  $Z_0 = 45$   
 —◆— Coplanar waveguide:  $w = 100.0 \mu\text{m}$ ,  $100.0 \mu\text{m}$ ,  $h = 127 \mu\text{m}$ ,  $Z_0 = 45$

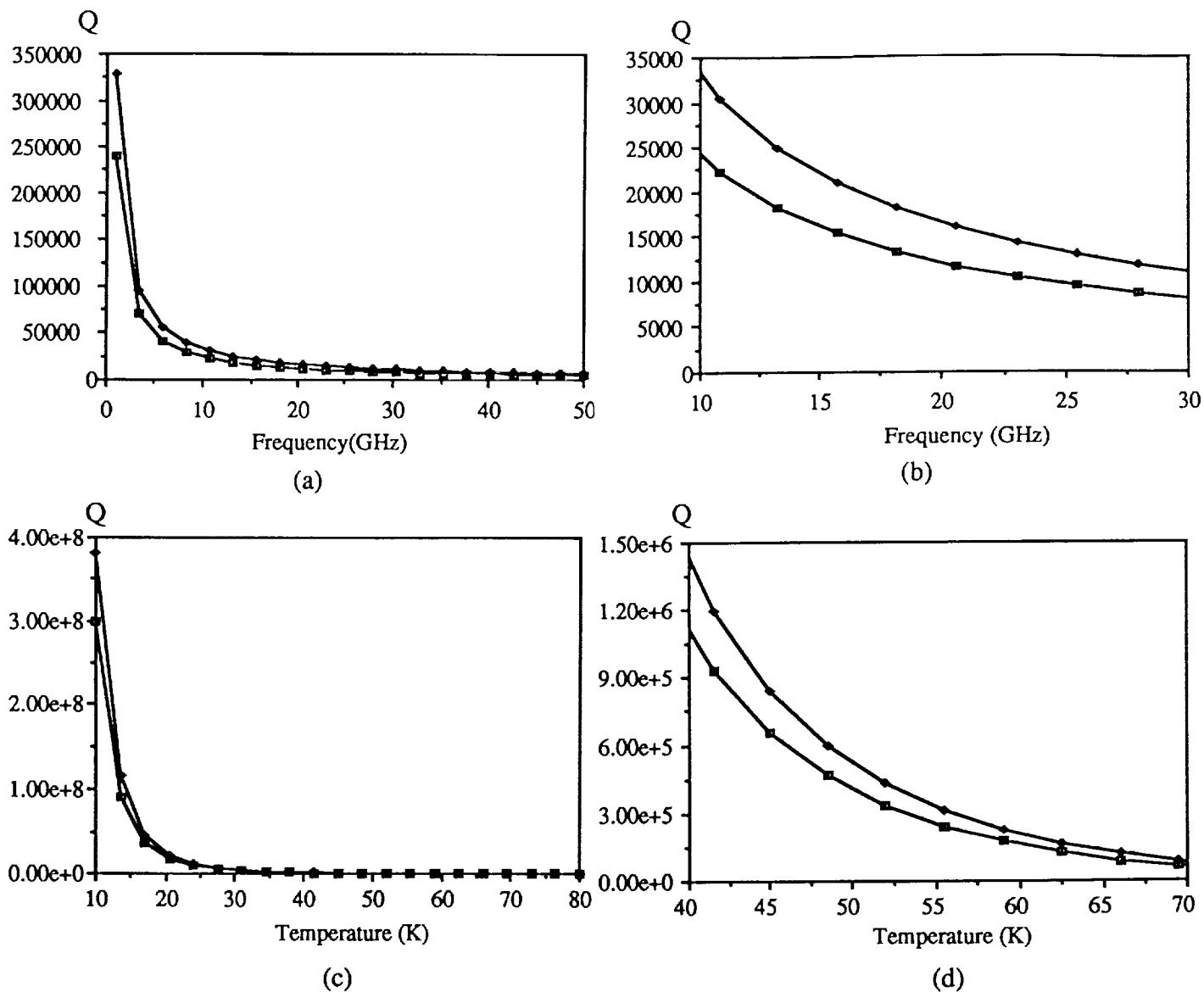
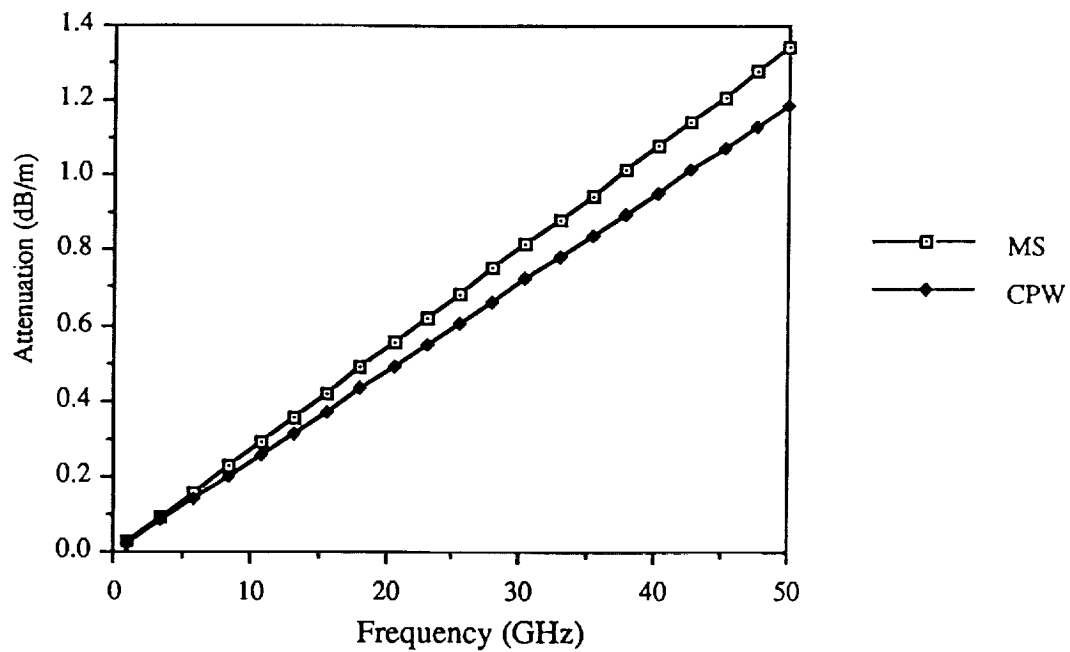


Fig. 5. Q values of the microstrip line and coplanar waveguide with same characteristic impedance but with wider dimension of the coplanar waveguide.  
 (Parameters of the material are shown in Fig. 1)  
 (a) Q with the variation of the frequency.  
 (b) Magnified view of (a) in the frequency region from 10 to 30 GHz.  
 (c) Q with the variation of the temperature.  
 (d) Magnified view of (c) in the temperature region from 40 to 70 K.



Microstrip Line:  $w = 90 \mu\text{m}$ ,  $h = 254 \mu\text{m}$ ,  $Z_0 = 50$

Coplanar Waveguide:  $w = 160 \mu\text{m}$ ,  $s = 100 \mu\text{m}$ ,  $h = 254 \mu\text{m}$ ,  $Z_0 = 50$

Fig. 6. The comparison of the substrate loss between the microstrip line and coplanar waveguide.

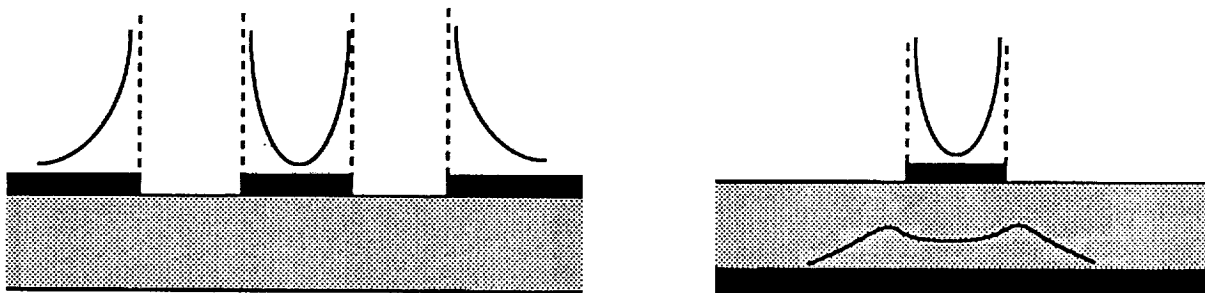


Fig.7 Current Distribution in the microstrip line and the coplanar waveguide.