

Characterization of Materials using Stripline Resonators

by

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(ABSTRACT)

This thesis describes a method for using stripline resonators to characterize the electrical properties of materials used in the construction of planar geometry transmission lines and circuits. The method characterizes both dielectric and conductor materials. It can be used to find the relative dielectric constant and to separate the conductor and dielectric losses. The separation of the loss terms is achieved by fitting measurements of stripline losses to a well known model. This model identifies the loss terms separately based on variation of the losses with stripline dimensions.

This thesis presents the complete stripline resonator model used. The model has been incorporated into a computer simulation which predicts the resonator response. This simulation is useful in many ways, including the design of various resonators needed in experiments. Also presented are the results of an experiment which demonstrates the feasibility of this method when applied to real samples. These results show that this method works well for low loss materials.

Further development may produce a model which will allow this method to be used on higher loss materials. A similar theoretical derivation may be used to develop a model

for using this method with other transmission line structures such as coaxial lines. This method is advantageous because it does not assume that material properties are independent of frequency and can be designed to produce results at a specific frequency. Stripline resonators are easily manufactured and a network analyzer is the only test equipment required. For these reasons, this method can be used to provide accurate results at a low cost.

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Chapter 1

Introduction

1.1 Background

Many different materials are used to construct microwave components such as transmission lines, filters, capacitors, inductors, and many others. To properly design these microwave components, it is important to know the characteristics of the construction materials at microwave frequencies. This chapter gives a summary of typical methods which are used for material characterization. This information provides the background for presenting the method used in this thesis which involves the use of a stripline resonator structure to characterize materials.

1.2 Summary of Test Methods

Characterization of materials at microwave frequencies generally requires finding the properties which describe both conductor and dielectric materials. Conductor materials are described by their conductivity. Dielectric materials may be described by their relative dielectric constant and dielectric loss tangent.

The two most commonly used techniques for measuring these properties at microwave frequencies are cavity techniques and transmission line techniques. Cavity methods involve modeling a cavity in some geometry with boundaries of finite conductivity filled with a lossy dielectric. This model is used to relate the measured resonant frequency and quality factor of a resonator to the characteristics of the materials from which it was constructed. Transmission line techniques use an assumed model for the response of a dielectric filled transmission line section and then use either time or frequency domain measurement techniques to match the response of a real transmission line to the model.

1.3 Stripline Characterization Methods

Characterization of materials using striplines is important because many of the materials used at microwave frequencies can be used to construct striplines. The geometry of a standard stripline is shown in figure 1.1. A low loss stripline can be modeled by assuming TEM propagation and using a standard lossy transmission line model; the transmission line can be characterized by a characteristic impedance Z_0 and a complex propagation constant $\gamma = \alpha + j\beta$. Using this model the material properties can be found by time or frequency domain measurements. These methods depend on the fact that the conductor loss and the dielectric loss vary differently with frequency in order to separate the loss terms from the total attenuation α .

1.4 Stripline Resonator Method

Accurately measuring the attenuation constant α of a short stripline may be difficult. For this reason it is desirable to construct a stripline resonator by placing two gaps in the center strip of the stripline. This arrangement is shown in figure 1.2. Using this method, the attenuation factor can be determined more accurately by measuring the quality factor of the resonator. The difficulty with

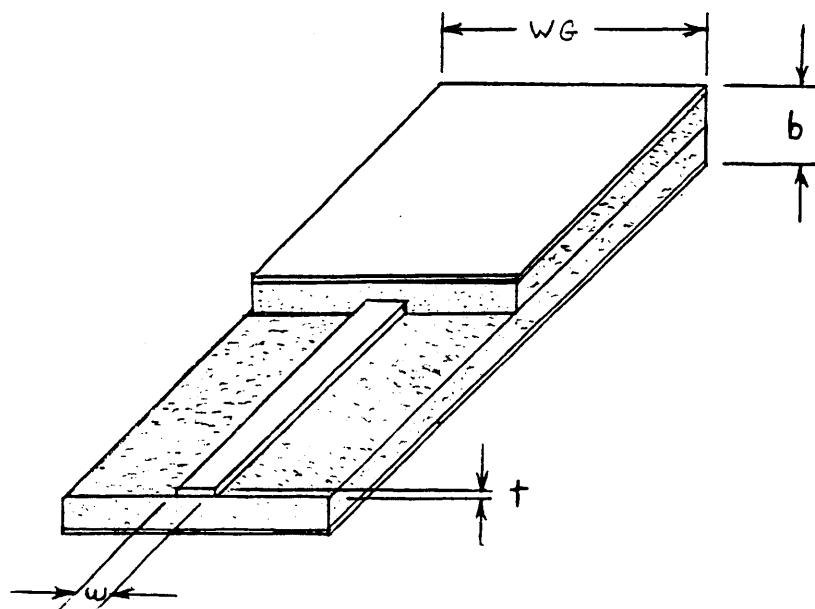


Figure 1.1: Standard stripline configuration.

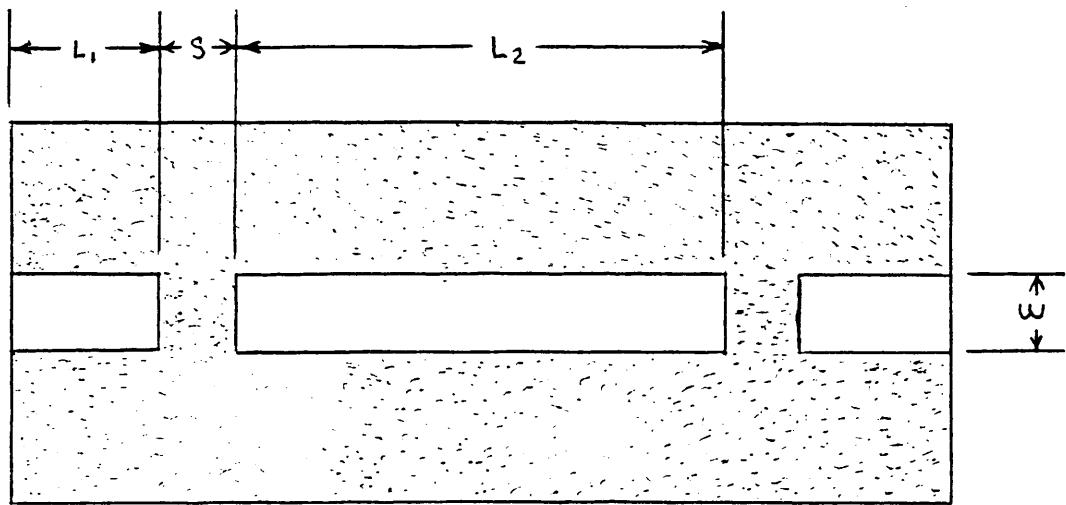


Figure 1.2: Stripline resonator configuration.

this method that it only provides the values of the attenuation factor at the resonant frequencies of the resonator and does not give continuous results to be used in separating the loss terms by assuming frequency dependence. A solution to this problem is to assume that the conductor loss varies as a function of the dimensions of the stripline. Since this variation can be characterized, the loss terms can be separated by constructing a series of resonators with varying stripline dimensions which all resonate at the same frequency. The quality factors of each of these resonators can be measured and the loss terms can be separated based on the variation of conductor loss with stripline dimensions. By measuring the resonant frequency of the resonators it is possible to estimate the relative permittivity of the dielectric. This method is advantageous because it gives the material characteristics at a specific frequency and produces correct results even with materials whose characteristics vary with frequency.

1.5 Summary

This thesis is divided into five chapters and two appendices. Chapter 1 has given an introduction to the stripline resonator method. Chapter 2 describes the theoretical method for separating the loss terms based on the variation of conductor loss with stripline dimensions. Chapter 2 also describes the method for estimating the relative permittivity based on the resonant frequency of the resonator. Chapter 3 describes the evolution of a computer program, called SRM,

which can be used to predict the response of stripline resonators. Chapter 4 gives the results of an experiment which was conducted to show the feasibility of this method. Chapter 5 gives a summary of the results and conclusions presented in this thesis. Appendix A describes the techniques used to produce striplines on printed circuit boards. Appendix B gives a detailed description of the operation of the SRM computer program.

Chapter 2

Material Characterization Method

2.1 Introduction

This chapter presents the equations and theory necessary to relate the response of a stripline resonator to the characteristics of the materials from which it is constructed. This derivation begins with equations for the computation of the characteristic impedance of striplines. These equations are used to derive a method for separating the loss terms based on the theoretical variation of conductor loss with stripline dimensions. This chapter also describes a method which relates the resonant frequency of the resonator to the relative permittivity of the dielectric.

2.2 Characteristic Impedance

For an ideal stripline with a zero-thickness, perfectly conducting center strip, the characteristic impedance is given exactly by [reference 1, page 119]

$$Z_o = \frac{30\pi K(k)}{\sqrt{\epsilon_r} K(k')} \quad (2.1)$$

where $K(x)$ is the complete elliptic integral of the first kind defined by

$$K(x) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1-x^2 \sin^2 \theta}} \quad (2.2)$$

and

$$k = \operatorname{sech} \frac{\pi w}{2b}, \quad k' = \tanh \frac{\pi w}{2b} \quad (2.3)$$

where w is the center strip width and b is the dielectric thickness. Although this formula is exact, it is not very useful because in reality, any center strip will have a finite thickness and conductivity.

There are a number of approximate formulas available which produce good results within limited ranges. One of the most useful of these is [2,90]

$$Z_o = \frac{30\pi \left[1 - \frac{t}{b}\right]}{\sqrt{\epsilon_r} \left[\frac{w_e}{b} + \frac{C_f}{\pi} \right]} \text{ ohms} \quad (2.4)$$

where

$$C_f = 2 \ln \left[\left[\frac{1}{1 - \frac{t}{b}} + 1 \right] - \frac{t}{b} \ln \left[\left[\frac{1}{1 - \frac{t}{b}} \right]^2 - 1 \right] \right] \quad (2.5)$$

and ϵ_r is the relative permittivity of the dielectric. The effective center strip width, w_e , is defined in the wide and narrow strip regions. In the wide strip region of $\frac{w}{(b-t)} \geq 0.35$, the effective center strip width, w_e , is defined by [2,90]

$$\frac{w_e}{b} = \frac{w}{b}. \quad (2.6)$$

This formula is accurate to 1 percent for $\frac{t}{b} \leq 0.25$. In the narrow strip region of $0.05 \leq \frac{w}{(b-t)} \leq 0.35$, the empirical formula,

$$\frac{w_e}{b} = \frac{w}{b} - \frac{\left[0.35 - \frac{w}{b}\right]^2}{1 + 12 \frac{t}{b}} \quad (2.7)$$

has been found to be within 1 percent of measured data for $\frac{t}{b} \leq 0.25$ [2,91].

Without this empirical correction factor, the expression is off by as much as 20 percent in the narrow strip region [2,91]. The formulas given above are the same as the formulas in Cohn, except that Cohn does not use the empirical correction for the narrow strip case [1,119]. Instead, Cohn uses an equivalent round conductor approximation for the narrow strip region of $\frac{w}{(b-t)} \leq 0.35$. His paper gives the narrow strip characteristic impedance as [1,119]

$$Z_o = \frac{60}{\sqrt{\epsilon_r}} \ln \left[\frac{4b}{\pi d_o} \right] \text{ ohms.} \quad (2.8)$$

where d_o is the diameter of an equivalent circular center conductor. This formula is said to be valid for $\frac{w}{(b-t)} \leq 0.35$ and $\frac{t}{b} \leq 0.25$. The value of d_o can be found from Figure 2.1 which is a plot of $\frac{d_o}{d'}$ versus $\frac{d''}{d'}$ where d'' is the smaller of the dimensions w and t and d' is the larger dimension.

For $\frac{d''}{d'} \leq 0.11$, a very good approximate formula for computing d_o is [1,122]

$$\frac{d_o}{d'} = \frac{1}{2} \left[1 + \frac{d''}{\pi d'} \left[1 + \ln \frac{4\pi d'}{d''} + 0.510 \left[\frac{d''}{d'} \right]^2 \right] \right]. \quad (2.9)$$

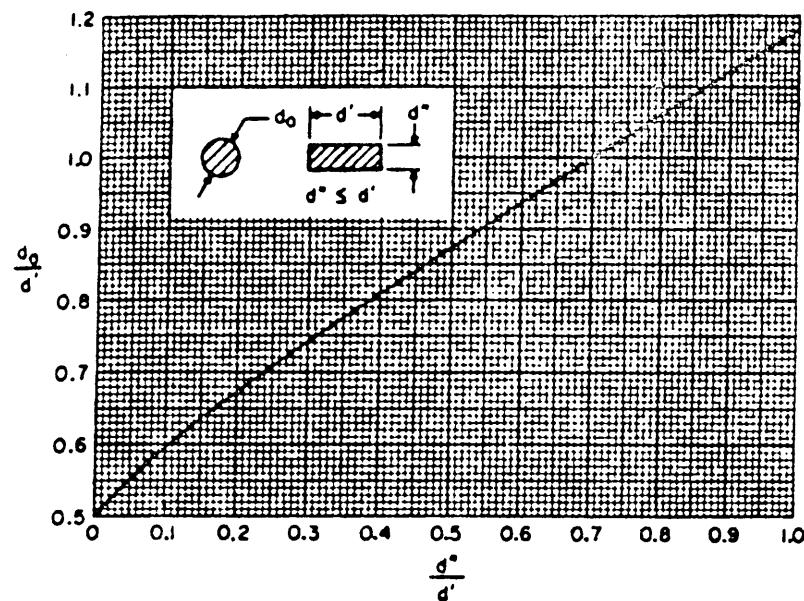


Figure 2.1: Equivalent round conductor diameter for a rectangular cross section

conductor [1,125].

2.3 Quality Factor in Stripline Resonators

The quality factor, Q_o , of a low loss stripline resonator can be expressed as

$$\frac{1}{Q_o} = \frac{1}{Q_c} + \frac{1}{Q_e} + \frac{1}{Q_r} + \frac{1}{Q_d} \quad (2.10)$$

where Q_c is the term due loss in the conductor, Q_e is the term due to end radiation loss, Q_r is the term due to side radiation loss and Q_d is the term due to the dielectric loss tangent [3,266]. Measurements have shown that for most cases, $\frac{1}{Q_e} + \frac{1}{Q_r}$ is less than 1 percent of the value of $\frac{1}{Q_o}$ [3,267]. Assuming these terms can be neglected, gives

$$\frac{1}{Q_o} \approx \frac{1}{Q_c} + \frac{1}{Q_d}. \quad (2.11)$$

The term Q_d is related directly to the dielectric loss tangent by the relation derived below. The dielectric attenuation α_d is related to (the dielectric loss tangent) $\tan\delta$ by [1,120]

$$\alpha_d = \frac{\pi}{\lambda} \sqrt{\epsilon_r} \tan\delta. \quad (2.12)$$

where λ is the wavelength in free space.

For the case where α (the attenuation of the line in nepers per unit length) is small the quality factor of a line resonator can be related to α by [6,429]

$$Q = \frac{\pi\sqrt{\epsilon_r}}{\alpha\lambda}. \quad (2.13)$$

This is a good approximation if $\alpha \ll \beta$ and $\alpha\ell \ll 1$, where ℓ is the length of the resonant transmission line, and α and β are the real and imaginary parts of the complex propagation constant defined by $\gamma = \alpha + j\beta$. Substituting equation 2.12 in equation 2.13 gives

$$\frac{1}{Q_d} = \tan\delta \quad (2.14)$$

which is the desired result.

It is now of interest to consider the conductor loss term. If α_c (attenuation due to conductor loss) is known, then $\frac{1}{Q_c}$ can be approximated using equation 2.13. It is possible to find α_c by considering the incremental change in inductance per incremental change in stripline dimensions [1,121]. This method gives [1,121]

$$\alpha_c = \frac{R_s\sqrt{\epsilon_r}}{753.2 \cdot Z_0} \frac{\delta Z_o}{\delta n} \left[\frac{\text{nepers}}{\text{unit length}} \right]. \quad (2.15)$$

The term R_s is the sheet resistivity of the cladding given by [2,91]

$$R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} \quad (2.16)$$

where f is the frequency, μ_0 is the permeability, and σ is the conductivity of the conductor. This derivation assumes a TEM wave propagation. In the case of a stripline [1,121]

$$\frac{\partial Z_o}{\partial n} = 2 \frac{\partial Z_o}{\partial b} - 2 \frac{\partial Z_o}{\partial w} - 2 \frac{\partial Z_o}{\partial t}. \quad (2.17)$$

Substituting equations 2.16 and 2.17 in equation 2.15 gives

$$\alpha_c = \frac{\sqrt{\pi f \epsilon_r \mu_0}}{376.6 \cdot Z_o \sqrt{\sigma}} \left[\frac{\partial Z_o}{\partial b} - \frac{\partial Z_o}{\partial w} - \frac{\partial Z_o}{\partial t} \right]. \quad (2.18)$$

Substituting equation 2.18 in equation 2.13 gives

$$\frac{1}{Q_c} = \frac{1.5911}{\sqrt{\sigma \cdot f}} \frac{1}{Z_o} \left[\frac{\partial Z_o}{\partial b} - \frac{\partial Z_o}{\partial w} - \frac{\partial Z_o}{\partial t} \right] \quad (2.19)$$

Where σ is the conductivity of the cladding in S/m, f is the frequency in GHz and the stripline dimensions b , t , and w are in cm. The mixed units are accounted for

in the constant 1.5911. This formula can be expressed in the more general form

$$\frac{1}{Q_e} = \frac{1.5911}{\sqrt{\sigma \cdot f}} g(b, t, w) \quad (2.20)$$

where

$$g(b, t, w) = \frac{1}{Z_o} \left[\frac{\partial Z_o}{\partial b} - \frac{\partial Z_o}{\partial w} - \frac{\partial Z_o}{\partial t} \right]. \quad (2.21)$$

2.4 Quality Factor Due to Conductor Loss

Using equation 2.21 it is now possible to find $g(b, t, w)$ for each of the given characteristic impedance equations. For the wide strip case, substituting equation 2.4 in equation 2.21 gives [1,121]

$$g_1(b, t, w) = \left[\frac{1 + \frac{2w}{b-t} + \frac{1}{\pi} \frac{b+t}{b-t} \ln \frac{2b-t}{t}}{w + \frac{2b}{\pi} \ln \frac{2b-t}{b-t} - \frac{t}{\pi} \ln \frac{t(2b-t)}{(b-t)^2}} \right]. \quad (2.22)$$

This equation is valid for $\frac{w}{b-t} \geq 0.35$ and $\frac{t}{b} \leq 0.25$ with $g_1(b, t, w)$ in $\frac{1}{cm}$.

Using the same method with the narrow strip characteristic impedance formula in equation 2.8 and the formula for equivalent center conductor diameter in equation

2.9 yields $g_2(b,t,w)$ given by [1,122]

$$g_2(b,t,w) = \frac{1}{b \cdot \ln \frac{4b}{\pi d_o}} \cdot \left[1 + \frac{b}{d_o} \left[\frac{1}{2} + k_1 \frac{d''}{d'} - k_2 \left[\frac{d''}{d'} \right]^2 + \frac{1}{2\pi} \ln \left[\frac{4\pi d'}{d''} \right] \right] \right]. \quad (2.23)$$

This is valid for $\frac{w}{b-t} \leq 0.35$, $\frac{t}{b} \leq 0.25$ and either $\frac{t}{w} \leq 0.11$ or $\frac{w}{t} \leq 0.11$ with $g_2(b,t,w)$ in $\frac{1}{cm}$ and $k_1=0.1592$ and $k_2=0.244$.

For the case of the empirical formula of equation 2.7 the computation of partial derivatives of Z_o is very complicated and it is easier to produce $g_3(b,t,w)$ by using numerical methods to compute the partial derivatives. Although it is not generally a good practice to take derivatives of an empirical formula, it will be shown in chapter 3 that this method produces reasonable results.

2.5 Method for Separating Loss Terms

By substituting equations 2.14 and 2.20 into 2.11 it is possible to write

$$\frac{1}{Q_o} = \frac{1.5911}{\sqrt{\sigma \cdot f}} g_x(b,t,w) + \tan\delta. \quad (2.24)$$

where $g_x(b,t,w)$ is one of functions given in the previous section with f in GHz, σ the conductivity of the cladding in S/m and $g_x(b,t,w)$ in $1/cm$ [3,266]. Plotting $\frac{1}{Q_o}$ versus $g_x(b,t,w)$ results in a straight line with a slope $m = \frac{1.5911}{\sqrt{\sigma \cdot f}}$ and a y-

intercept $b=\tan\delta$ [3,266]. This gives a method for separating the loss terms by producing multiple stripline resonators and plotting their unloaded quality factors versus $g_x(b,t,w)$.

2.6 Method for Estimating Dielectric Constant

The relative permittivity of the dielectric can be estimated using a stripline resonator. This is because the equivalent length of the center strip of the resonator must be an integer multiple of the waveguide half-wavelength $\frac{\lambda_g}{2}$ at the resonant frequency. Assuming TEM propagation this can be written as

$$\frac{\lambda_g}{2} = \frac{c}{2f_r\sqrt{\epsilon_r}} = n(L') = n(L_2 + 2\Delta L) \quad (2.25)$$

where c is the speed of light in free space, f_r is the resonant frequency, ϵ_r is the relative permittivity, L' is the effective center strip length, L_2 is the actual center strip length, ΔL is the length correction factor to account for fringing and $n=1,2,3\dots$ is the order of the resonance. It is reasonable to assume that the correction factor ΔL must lie in the range $0 \leq \Delta L \leq \frac{s}{2}$ where s is the gap width. Using this assumption, the relative permittivity is bounded by $\epsilon_1 \leq \epsilon_r \leq \epsilon_2$ where ϵ_1 is found using equation 2.24 with $\Delta L=0$ and ϵ_2 is found using equation 2.24 with $\Delta L=\frac{s}{2}$. This range of values can be made smaller by making the gap width smaller, but this increases the loading of the resonator.

2.7 Summary

Based on the information presented previously in this chapter, it is possible to construct a series of stripline resonators to characterize the material from which they are constructed. The most important factor in designing this series of stripline resonators is that the dimensions be varied sufficiently such that a good plot of $\frac{1}{Q_o}$ versus $g_x(b,t,w)$ can be obtained. Since the thickness of the dielectric determines the b dimension and the thickness of the metal cladding determines the t dimension, it is not feasible to vary either of these two dimensions. This means that a series of resonators must be designed with varying center strip widths, w. The length, L_2 , of the center strip must be chosen so that one of the resonant frequencies occurs at the frequency at which the material properties are to be characterized. The gap is chosen to be wide enough to reduce loading effects to an acceptable level while keeping the resonance within the dynamic range of the test equipment. Designing a suitable series of resonators can be carried out using the computer simulation described in chapter 3.

Chapter 3

SRM Computer Simulation

3.1 Introduction

In order to design a series of resonators which will produce good experimental results, it is desirable have a computer program which can predict the response of stripline resonators. This has been accomplished in the computer program SRM (Stripline Resonator Model). The details of the design of this program are shown in this chapter and the program code is listed in appendix B.

3.2 Theoretical Basis for Computer Simulation

A stripline resonator connected to a network analyzer can be modeled using S-parameters. By assuming TEM propagation, a stripline can be modeled by a lossy transmission line. The gap discontinuity can be modeled as a pi-network [4,142]. The network analyzer can be modeled by placing 50 ohm terminations at both ends of the resonator.

In order to model the stripline as a lossy transmission line, it is necessary to know the characteristic impedance (Z_0) and the complex propagation constant (γ). The characteristic impedance is calculated using equation 2.4 for the wide strip case and equation 2.7 for the narrow strip case. The complex propagation constant is defined as

$$\gamma = \alpha + j\beta \quad (3.1)$$

where α is the line attenuation in nepers per unit length. The phase constant β is given by

$$\beta = \frac{2\pi}{\lambda_g} \left[\frac{\text{radians}}{\text{unit length}} \right] \quad (3.2)$$

where ϵ_r is the relative dielectric constant and $\lambda_g = \frac{\lambda}{\sqrt{\epsilon_r}}$ is the wavelength in the dielectric when λ is the wavelength in free space. In order to compute α , it is

necessary to relate it to the unloaded quality factor of the resonator. For $\alpha \ll \beta$ and $\alpha \cdot L_2 \ll 1$ this can be approximated using [6,429]

$$\alpha = \frac{\pi}{Q_o \lambda_g} \quad (3.3)$$

where Q_o is calculated using equation 2.24. For this case $g_x(b,t,w)$ is calculated using the two formulas for Z_o cited above and taking numerical partial derivatives. The above formulas give an entire method for numerically modeling a stripline resonator as a lossy transmission line connected to a network analyzer.

3.3 S-parameter Model

A stripline resonator system can be modeled by finding the S-parameters for each element and combining them to find the S-parameters of the entire system. The S-parameter model for a lossy line segment is shown in Figure 3.1 and the S-parameters for this model are given by [5,38]

$$[S] = \frac{1}{D_s} \begin{bmatrix} (Z^2 - Z_o^2) \cdot SH & 2ZZ_o \\ 2ZZ_o & (Z^2 - Z_o^2) \cdot SH \end{bmatrix}$$

where $SH = \sinh(\gamma l)$, $CH = \cosh(\gamma l)$, and $D_s = 2ZZ_o CH + (Z^2 + Z_o^2)SH$.

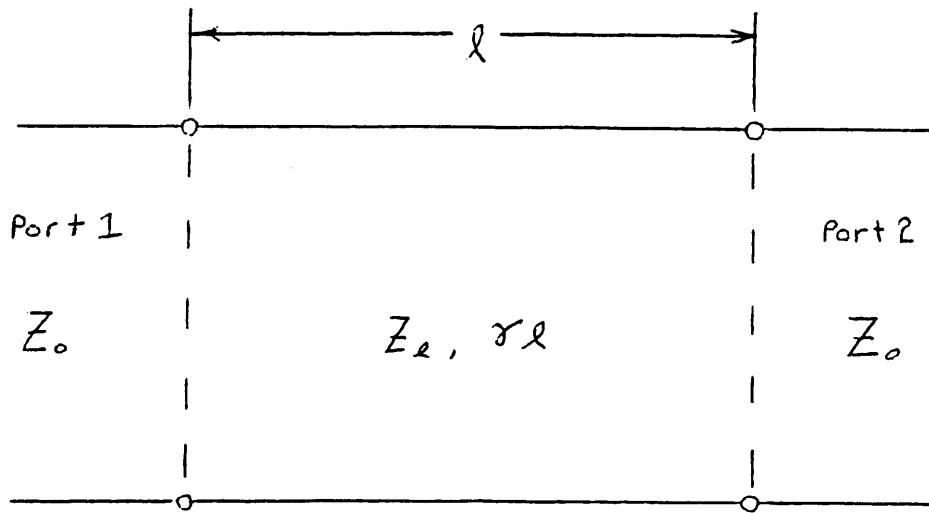


Figure 3.1: S-parameter model for a lossy line segment [5,38].

As mentioned previously, the gap discontinuity can be modeled by a π -network.

The model for this network is shown in figure 3.2. The reactances of the elements in this model are given by [4,142]

$$B_a = -Y_o \frac{2b}{\lambda_g} \ln \left[\cosh \frac{\pi s}{2b} \right] \quad (3.4)$$

and

$$B_b = Y_o \frac{b}{\lambda_g} \ln \left[\coth \frac{\pi s}{2b} \right] \quad (3.5)$$

where $Y_o = \frac{1}{Z_o}$ is the inverse of the characteristic impedance of the stripline, b is the dielectric thickness, and s is the gap width. The S-parameters of the π -network shown in figure 3.3 are given by [5,40]

$$[S] = \frac{1}{D_s} \begin{bmatrix} Y_o^2 - PY_o - D & 2Y_o Y_3 \\ 2Y_o Y_3 & Y_o^2 + PY_o - D \end{bmatrix} \quad (3.6)$$

where $D_s = Y_o^2 + QY_o + D$, $D = Y_1 Y_2 + Y_2 Y_3 + Y_3 Y_1$, $Q = Y_1 + Y_2 + 2Y_3$ and $P = Y_1 - Y_2$. Letting $Y_1 = Y_2 = 0 + jB_a$ and $Y_3 = 0 + jB_b$ and substituting this in equation 3.6 gives the S-parameters of the gap discontinuity.

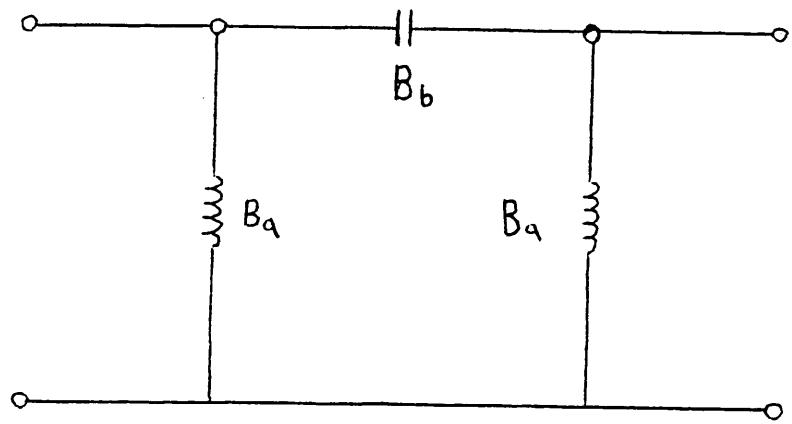


Figure 3.2: Equivalent reactance π -network model for a stripline gap [4,142].

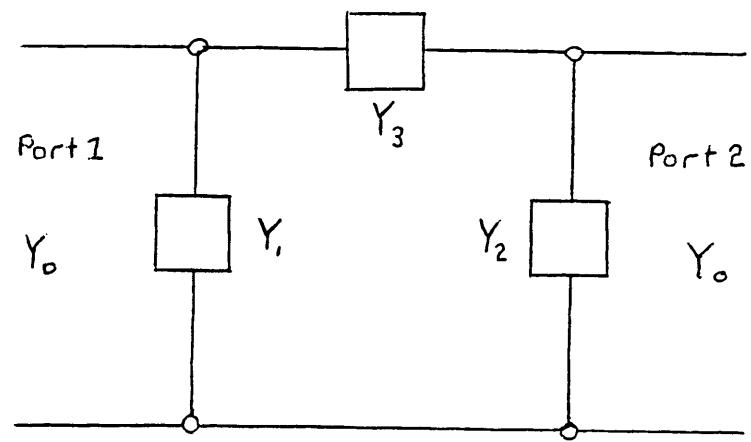


Figure 3.3: S-parameter model for a pi-network [5,40].

The model for the S-parameters of the discontinuity at a change in characteristic impedance is shown in figure 3.4 where the S-parameters are given by

$$[S] = \frac{1}{D_s} \begin{bmatrix} Z_2 - Z_1 & 2\sqrt{Z_1 Z_2} \\ 2\sqrt{Z_1 Z_2} & Z_1 - Z_2 \end{bmatrix} \quad (3.7)$$

where $D_s = Z_1 + Z_2$.

By chaining together seven sets of S-parameters it is possible to find the S-parameters of a stripline resonator connected to a network analyzer. This is done by separately computing the S-parameters ($[S_1]$ - $[S_7]$) of each of the sections. Since S-parameters cannot be cascaded directly, it is necessary to convert each of these seven matrices to equivalent T-parameter ($[T_1]$ - $[T_7]$) matrices using [5,37]

$$S_{11} = \frac{T_{12}}{T_{22}} \quad (3.8)$$

$$S_{12} = T_{11} - \left[\frac{T_{12} T_{21}}{T_{22}} \right] \quad (3.9)$$

$$S_{21} = \frac{1}{T_{22}} \quad (3.10)$$

$$S_{22} = -\frac{T_{12}}{T_{22}} \quad (3.11)$$

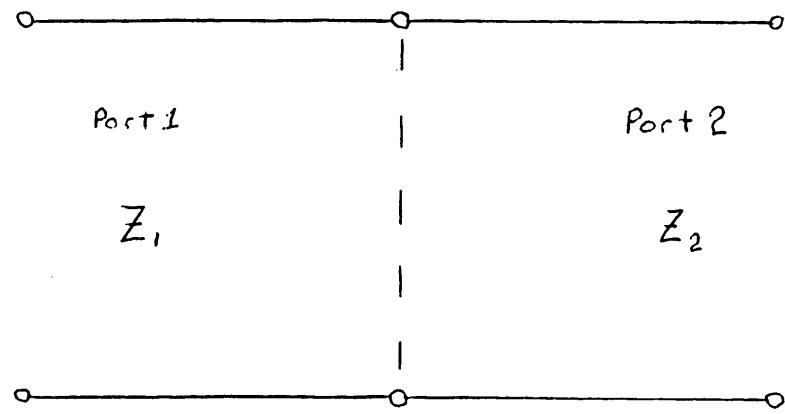


Figure 3.4: S-parameter model for a discontinuity in characteristic impedance [5,42].

The equivalent T-parameter matrices can be combined using

$$[T] = [T_1] [T_2] [T_3] [T_4] [T_5] [T_6] [T_7] \quad (3.12)$$

The combined T-parameter matrix can be converted back to an S-parameter matrix using [5,36]

$$T_{11} = \frac{S_{12}S_{21} - S_{11}S_{22}}{S_{21}} \quad (3.13)$$

$$T_{12} = \frac{S_{11}}{S_{21}} \quad (3.14)$$

$$T_{21} = -\frac{S_{22}}{S_{21}} \quad (3.15)$$

$$T_{22} = \frac{1}{S_{21}} \quad (3.16)$$

This gives the values of the S-parameters for a stripline resonator connected to a network analyzer at the frequency at which λ_g was calculated.

The computer program uses the above method to plot S-parameters versus frequency. By plotting $20 \cdot \log_{10}|S_{21}|$ versus frequency and finding the 3-dB points

of the resonance, it is possible to compute the loaded quality factor (Q_L) of the resonator using

$$Q_L = \frac{f_r}{[f_2 - f_1]} \quad (3.17)$$

where f_r is the resonant frequency and f_1 and f_2 are the frequencies of the lower and upper 3-dB points, respectively. The unloaded quality factor of the resonator can be theoretically calculated from

$$\frac{1}{Q_o} = \frac{|S_{22}|^2}{Q_L} - \frac{1 - |S_{22}|^2}{n\pi} \quad (3.18)$$

where S_{22} is the reflection parameter of the test setup as seen from the resonator section at the gap and n is the order of the resonance. The parameter S_{22} can be calculated using the S-parameter model shown previously. The computer program uses equation 3.18 to calculate the unloaded quality factor. In the case where the stripline has the same characteristic impedance as the network analyzer, the the unloaded Q can be approximated by

$$\frac{1}{Q_o} = \frac{1}{Q_L} [1 - |S_{21}|]. \quad (3.19)$$

Since the parameter S_{22} cannot be measured, it is desirable to make the gap large so that the magnitude of S_{21} is approximately equal to zero. For this case Q_o is approximately equal to Q_L . Since the computer program can be used to estimate the true unloaded quality factor, it can be used to estimate the magnitude of the error involved in assuming that the loaded and unloaded quality factors are equal.

3.4 Computer Simulation of a Typical Experiment

The computer program SRM uses the following parameters to model a stripline resonator:

- b = the dielectric thickness
- t = the conductor thickness
- w = the strip width
- s = the gap width
- L_1 = the launching strip length
- L_2 = the resonator strip length
- ϵ_r = the relative dielectric constant
- σ = the conductivity of the conductor
- $\tan\delta$ = the loss tangent of the dielectric

To study the accuracy of the stripline model, it is desirable to simulate a typical series of resonators with the SRM simulation by doing the following:

- 1) Enter the parameters of a series of resonators to the program.
- 2) The program computes values of $|S_{21}|$ versus frequency.

- 3) The program finds the resonant frequency and 3 dB bandwidth of each resonator and uses these to estimate the quality factor using $Q = \frac{f_r}{BW_{3dB}}$.
- 4) The program plots the inverse quality factors versus $g(b,t,w)$ to find the loss parameters.
- 5) The loss parameters found in part 4 can be compared to those entered in part 1.

The loss terms in parts 1 and 4 should be different because of the approximate formulas used to relate attenuation to quality factor. The parameters used for this example are $b=100$ mils, $t=2.0$ mils, $w=20, 40, 60, 80, 100$ mils, $s=140$ mils, $L_1=150$ mils, $L_2=1000$ mils, $\epsilon_r=10$, $\sigma=5.0 \times 10^7$ S/m and $\tan\delta=0.0010$. The results of simulating these resonators with SRM are shown in table 3.1. The magnitude of the resonance for each of the resonators is about -55 dB which indicates that there is very little loading. The values of $g(b,t,w)$ show a wide variation which is necessary to make a good line fit to the data points in the plot of $\frac{1}{Q_o}$ versus $g(b,t,w)$ shown in figure 3.5.

Table 3.1: Values of f_r in GHz, $|S_{21}|$, Z_o in ohms, $g(b,t,w)$ in $1/\text{cm}$, Q_ℓ ,
and Q_o for each of the resonator widths.

w	f_r	$ S_{21} $	Z_o	$g(b,t,w)$	Q_ℓ	Q_o
20	8.836	-56.82	44.94	20.48	370.65	371.19
40	8.836	-54.42	33.65	15.14	440.28	441.11
60	8.836	-53.77	27.35	13.81	461.91	462.85
80	8.836	-53.56	23.03	12.90	478.16	479.15
100	8.836	-53.61	19.89	12.24	490.36	491.38

$1/Q_o$ versus $g(b,t,w)$

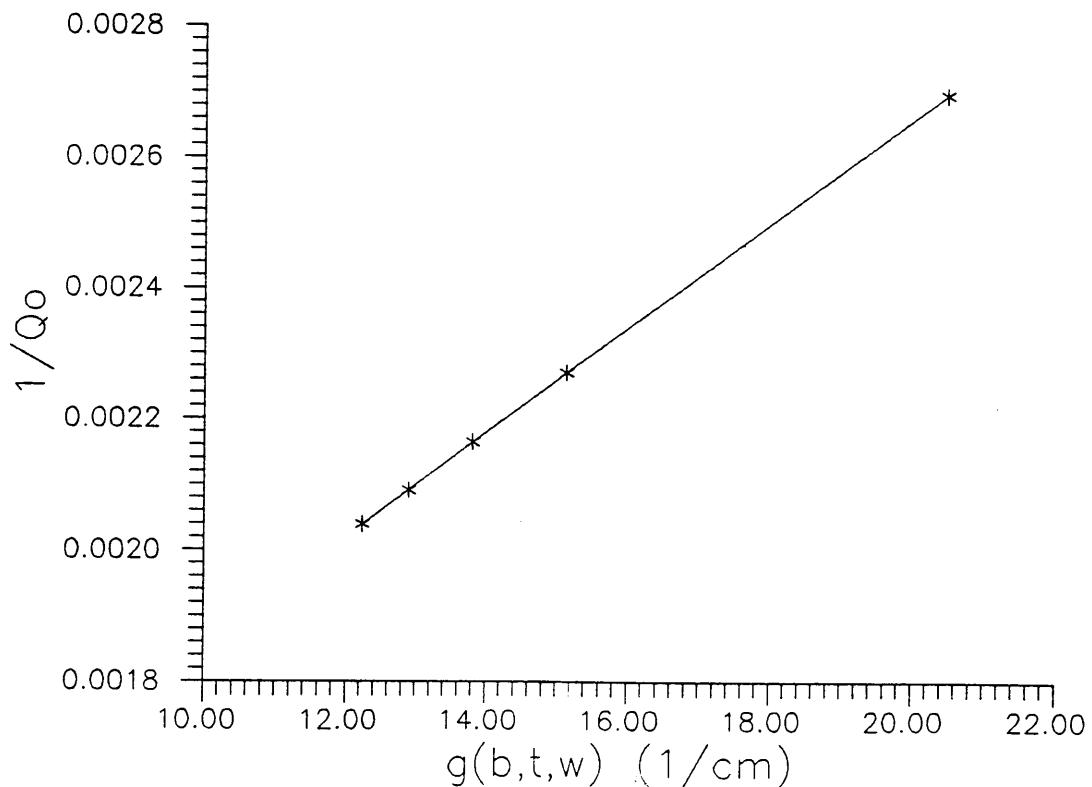


Figure 3.5: Plot of $\frac{1}{Q_o}$ versus $g(b,t,w)$ for the simulated experiment including a straight line fit to the data points.

Table 3.1 shows that the resonators of this simulated experiment do not have a 50 ohm characteristic impedance. It also shows that the error produced by assuming that Q_ℓ is equal to Q_o is small. Figure 3.5 is a plot of $\frac{1}{Q_o}$ versus $g(b,t,w)$. The straight line fit to this data indicates that $\sigma=4.448\times 10^7$ S/m and $\tan\delta=0.001061$. These values indicate a 11.1% error in calculating σ and a 6.1% error in calculating the value of $\tan\delta$ relative to the original assumed values. These errors are the result of using approximate formulas to relate quality factor to attenuation in the model. These types of errors in estimating loss parameters will be present in trying to characterize real materials because the model does not exactly predict the resonator response. The magnitude of these errors will become greater as the loss in the line becomes greater.

3.5 Sensitivity Analysis

In order to design a series of resonators, it is important to know the the sensitivity of the resonator response to the values of the design variables. The six variables which are important in designing a resonator are the relative permittivity ϵ_r , the center strip length L_2 , the gap width s , the dielectric thickness b , the conductor thickness t , and center strip width w . The parameters ϵ_r , L_2 and s have a great effect on the response of the resonator but no effect on the quality factor. For this reason, it is important to study the effect changing these parameters has on the resonator response. To do this, plots are made of the response of the resonator while varying each parameter separately. These results are shown in figures 3.6, 3.7, and 3.8.

Figure 3.6 shows that varying s affects both the resonant frequency and the maximum magnitude of the resonance. The resonant frequency changes because changing s changes the effective length of the center strip due to fringing. The magnitude of the resonance changes because the gap coupling is depends on s . The magnitude of the resonance decreases with increasing gap length as expected.

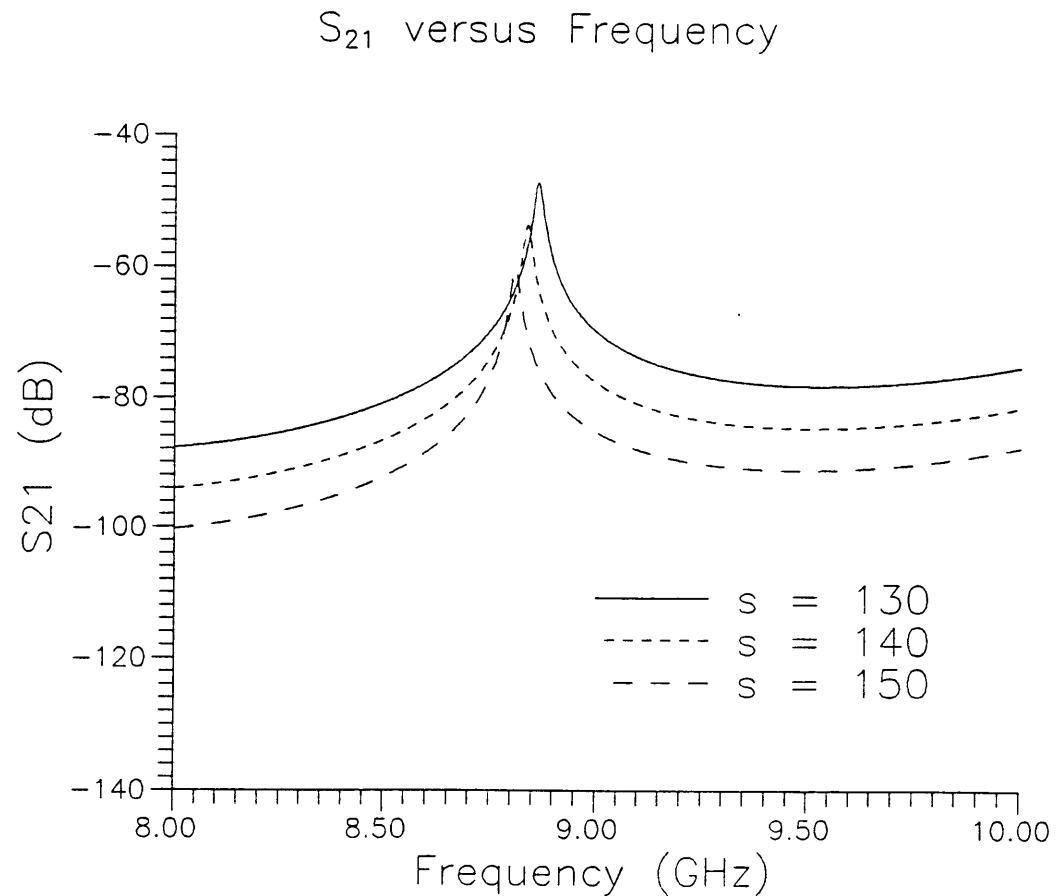


Figure 3.6: Plot of S₂₁ versus frequency for s=130,140,150 mils with b=100 mils, t=2 mils, w=100 mils, L₂=1000 mils, $\epsilon_r=10.0$, $\sigma=5.0e7$, and $\tan\delta=0.0010$.

S_{21} versus Frequency

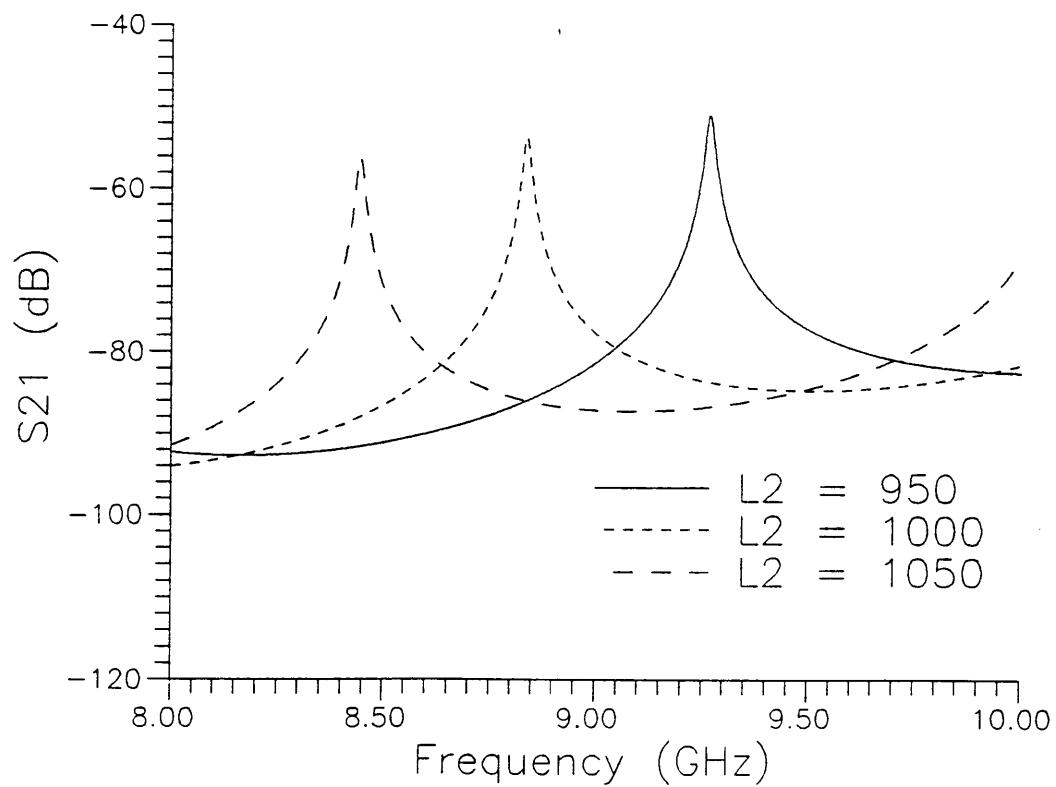


Figure 3.7: Plot of S_{21} versus frequency for $L_2=950, 1000, 1050$ mils with
 $b=100$ mils, $t=2$ mils, $w=100$ mils, $s=140$ mils, $\epsilon_r=10.0$,
 $\sigma=5.0e7$, and $\tan\delta=0.0010$.

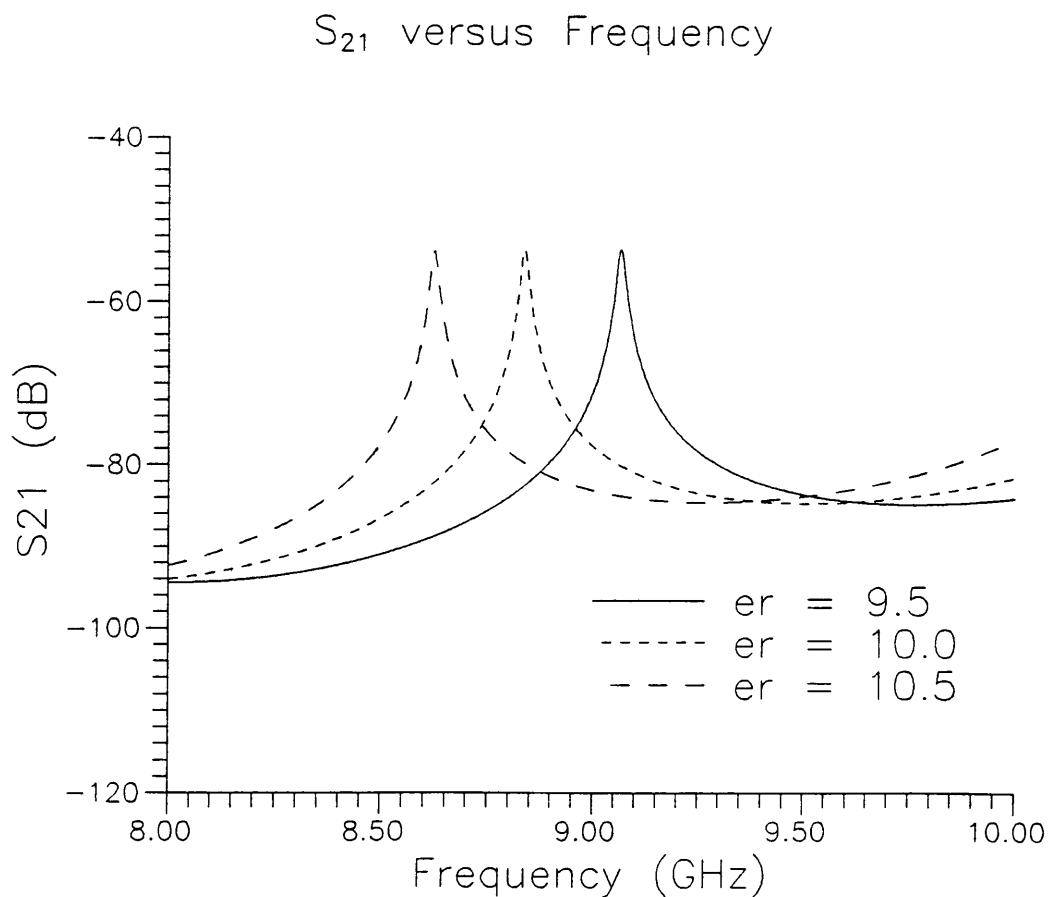


Figure 3.8: Plot of S₂₁ versus frequency for $\epsilon_r=9.5,10.0,10.5$ with b=100 mils, t=2 mils, w=100 mils, L₂=1000 mils, s=140 mils, $\sigma=5.0e7$, and $\tan\delta=0.0010$.

Figure 3.7 shows that varying the center strip length does not greatly affect the magnitude of the resonance but has a great effect on the value of the resonant frequency. This is expected because the center strip length does not affect coupling but is a major factor in determining the resonant frequency.

Figure 3.8 shows that varying ϵ_r has a similar effect to that of varying the center strip length. This is because changing ϵ_r changes the wavelength in the stripline. The plot shows that increasing the relative dielectric constant decreases the resonant frequency as expected.

The parameters b , t , and w do not greatly affect the response of the resonator, but they do have a great affect on the characteristic impedance of the line and on the conductor attenuation function $g_x(b,t,w)$. For this reason it is important to plot Z_o and $g_x(b,t,w)$ versus each of the parameters b , t , and w while holding the other two parameters constant. These plots also show a comparison of the values of $g(b,t,w)$ in the narrow strip region computed by taking numerical derivatives of an empirical formula (labeled numerical) and computed by taking analytical derivatives of the equivalent round conductor formula (labeled analytical) as described in chapter 2. These plots show that the two methods give similar results away from the transition at $\frac{w}{(b-t)} = 0.35$ and that the numerical method appears to give better results near this transition. These results are shown in figures 3.9-3.14.

$g(b,t,w)$ versus b for $w=25, t=1$

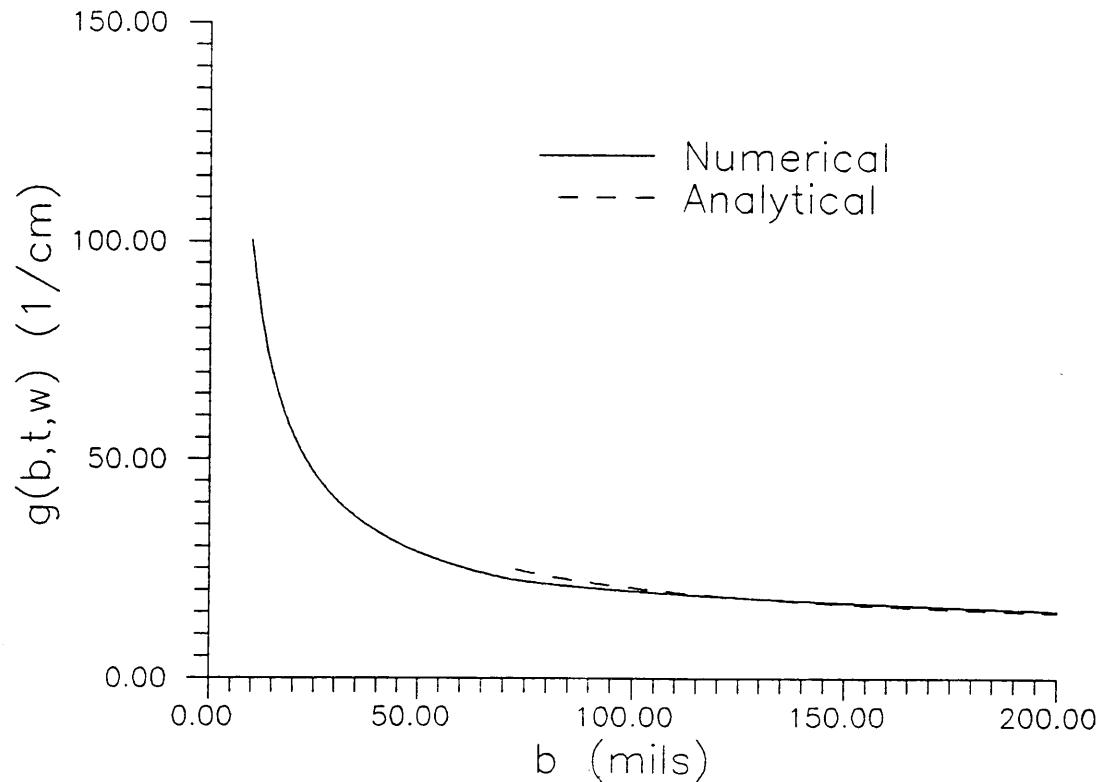


Figure 3.9: Plot of $g(b,t,w)$ versus b with $\epsilon_r=2.0$, $w=25$ mils,

$t=1$ mil.

$g(b,t,w)$ versus t for $b=100, w=25$

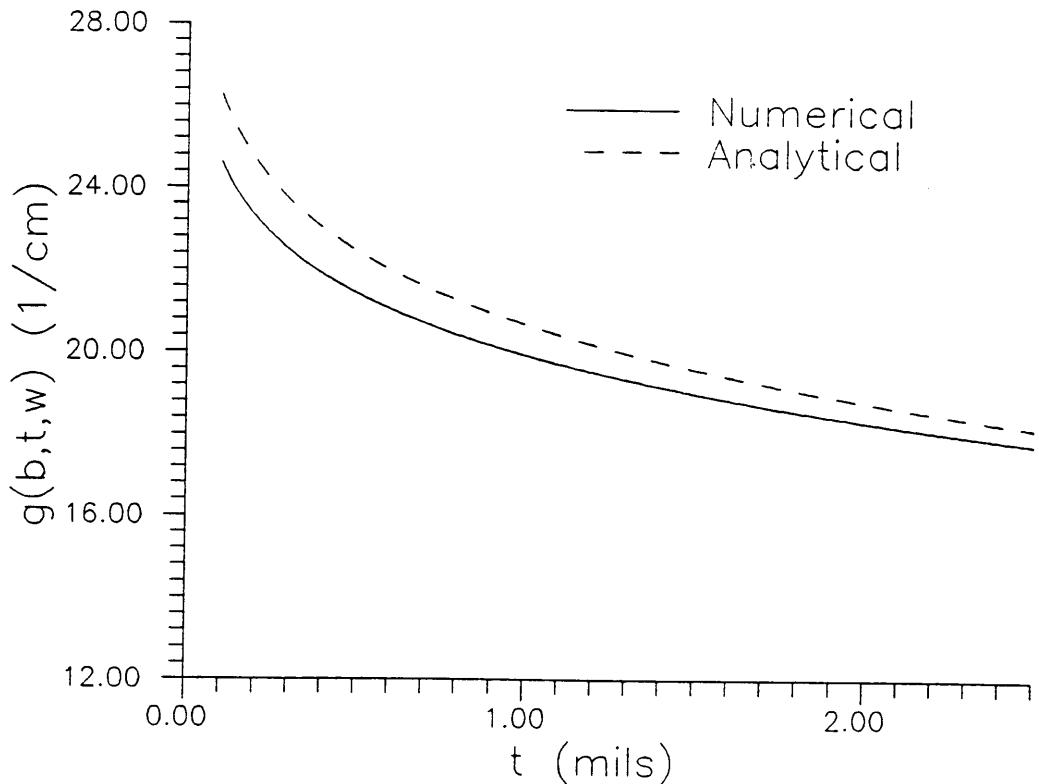


Figure 3.10: Plot of $g(b,t,w)$ versus t with $\epsilon_r=2.0$, $b=100$ mils,

$w=25$ mils.

$g(b,t,w)$ versus w for $b=100, t=1$

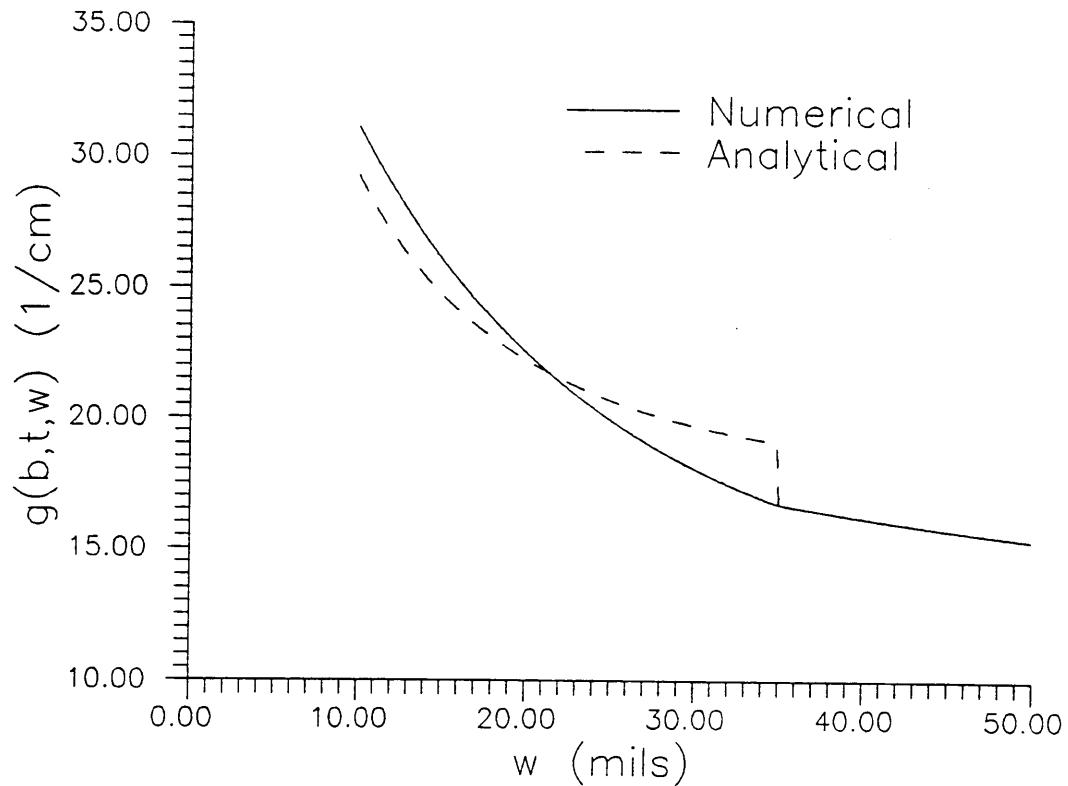


Figure 3.11: Plot of $g(b,t,w)$ versus w with $\epsilon_r=2.0$, $b=100$ mils,

$t=1$ mil.

Z_o versus b for $w=25, t=1$

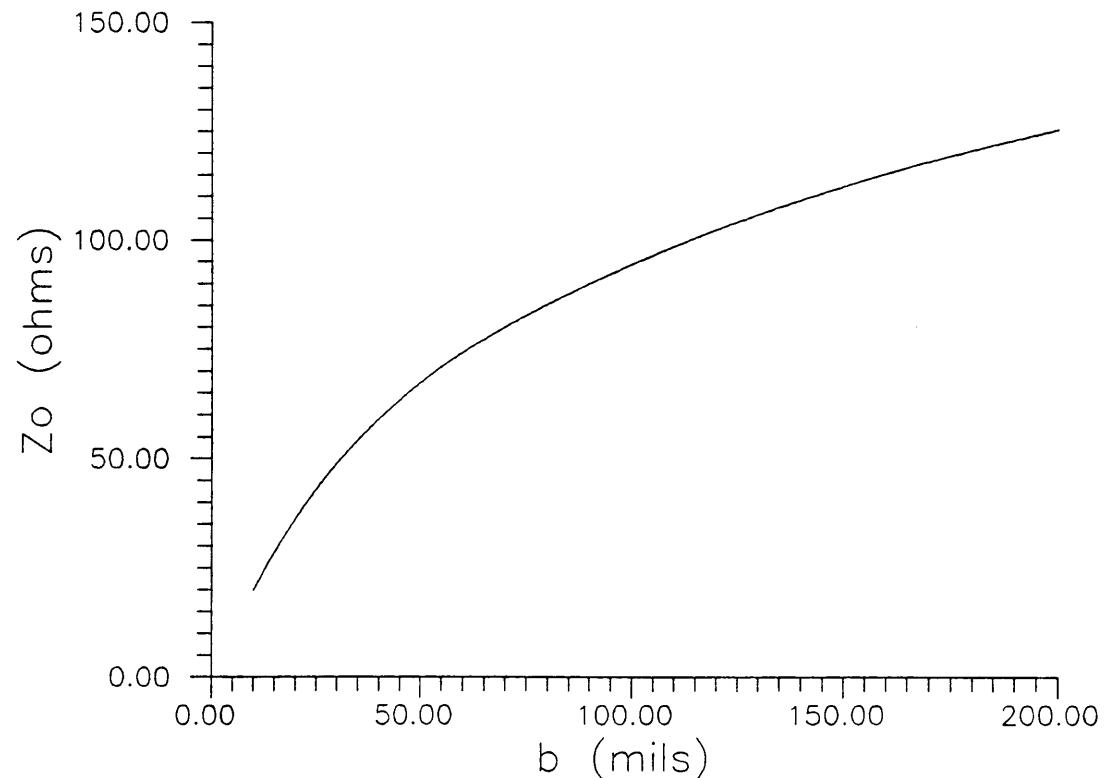


Figure 3.12: Plot of Z_o versus b with $\epsilon_r=2.0$, $w=25$ mils,

$t=1$ mil.

Z_o versus t for $b=100, w=25$

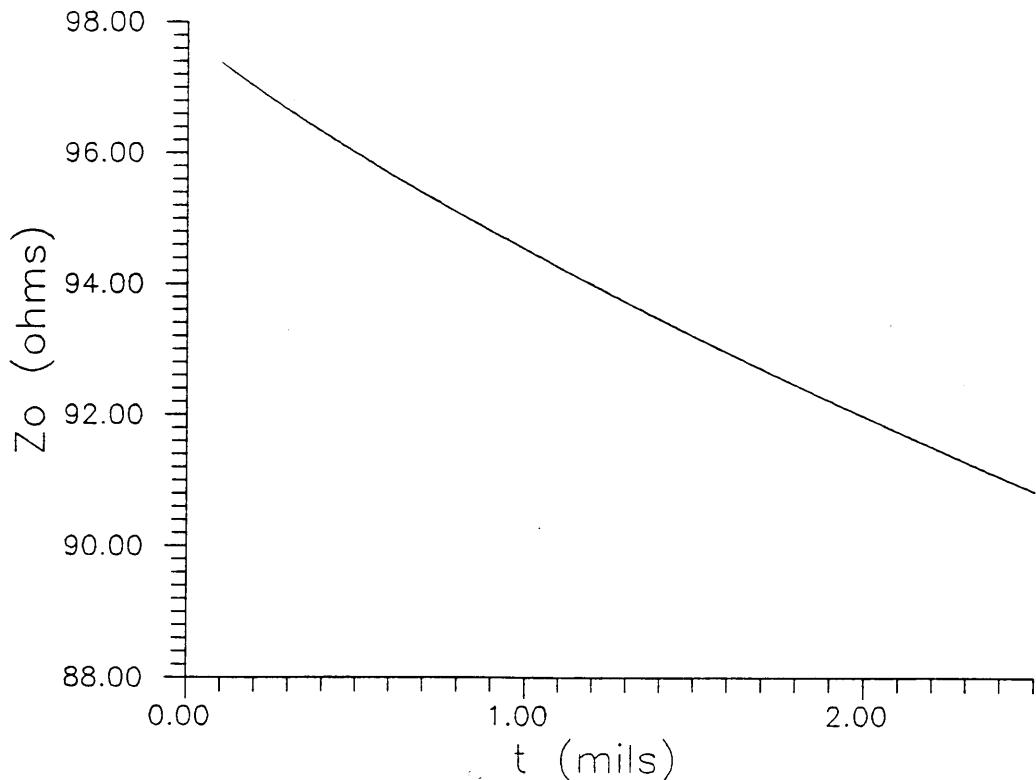


Figure 3.13: Plot of Z_o versus t with $\epsilon_r=2.0$, $b=100$ mils,

$w=25$ mils.

Z_o versus w for $b=100, t=1$

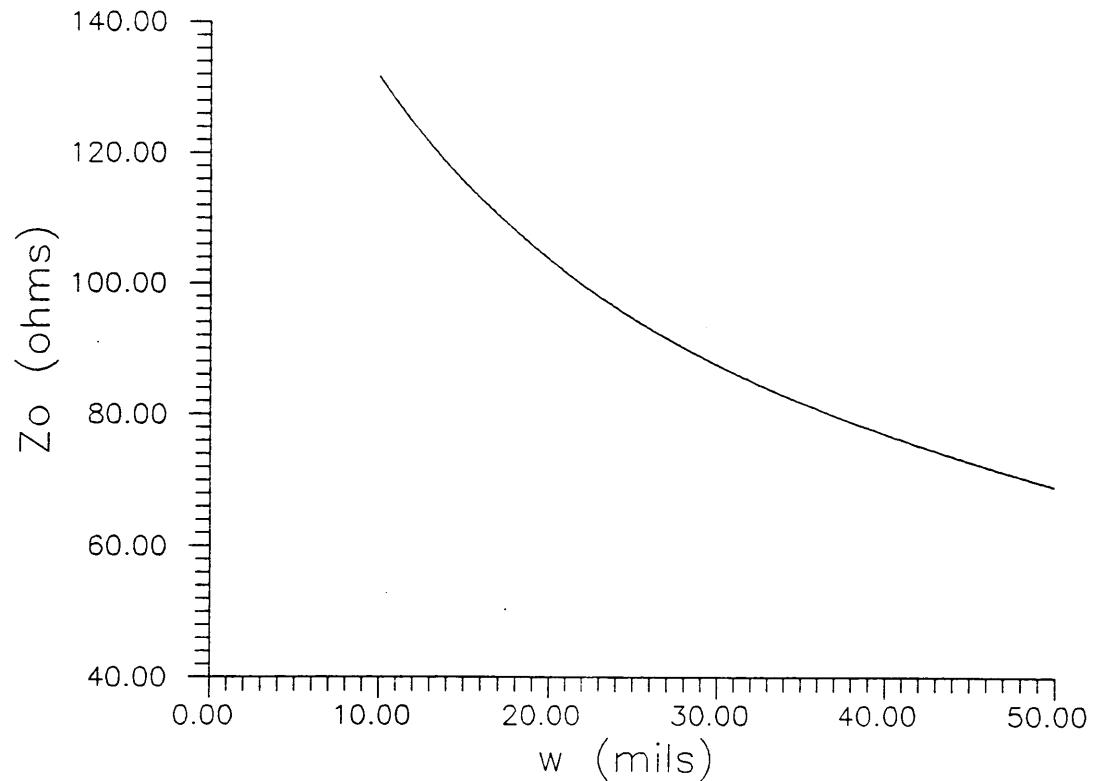


Figure 3.14: Plot of Z_o versus w with $\epsilon_r=2.0$, $b=100$ mils,

$t=1$ mil.

The plots of the variation of $g_x(b,t,w)$ with b , t , and w are important in designing a series of test resonators. If the series is designed in a region where $g_x(b,t,w)$ varies quickly with changes in stripline dimensions then a small error in the determination of the dimensions of a resonator will cause a great error in the value of $g_x(b,t,w)$. This is important because accurate determination of the loss parameters depends on an accurate calculation of $g_x(b,t,w)$. If the series is designed in a region where $g_x(b,t,w)$ varies slowly with changes in stripline dimensions then the values of $g_x(b,t,w)$ will be closely grouped and a good line fit to the data will not be possible. The plots of the variation of Z_o are important because they show the variation of Z_o in the region where the series is designed.

3.6 Summary

These results indicate that the computer program SRM is useful as a tool for designing stripline resonators. This program can be used to design the response of individual resonators or to design the response of an entire series of resonators. The method for using SRM is described in appendix B. This appendix also includes a listing of the source code for the program.

Chapter 4

Experimental Results

4.1 Introduction

Chapter 2 described the method for characterizing materials by producing multiple stripline resonators and measuring their dimensions and unloaded quality factors. The computer simulation SRM can be used to design an appropriate set of test resonators. This chapter describes a method for measuring stripline resonators and for reducing the data to find the material parameters. This chapter also describes the results of experiments conducted on materials with known properties. These experiments are used to prove the validity of the method and to verify the feasibility of the test method. This chapter also includes experiments conducted to characterize materials with unknown properties.

4.2 Measurement Techniques

Stripline resonators can be constructed from printed circuit boards using the method described in appendix A. In order to measure these stripline resonators, the two boards need to be clamped tightly together to eliminate air gaps and connectors need to be affixed so that the stripline can be connected to the network analyzer test leads. The boards are clamped together using a vise with rubber jaws to provide even pressure. In order to provide clamping force in the area of the connectors, two plexiglass pieces are used to place even pressure on the boards. The clamping force should be just great enough to eliminate all air gaps without deforming the dielectric. This force can be determined by attaching the stripline to the network analyzer and increasing the clamping force until no appreciable change in the waveform with increasing pressure. In order to connect the striplines to a network analyzer, ELJ connectors produced by Omni-spectra are used. The above setup is used to connect the striplines to an HP8510 network analyzer. The network analyzer is used to measure the resonant frequency and the loaded quality factor of the resonator. The unloaded quality factor of the resonator can be theoretically calculated from

$$\frac{1}{Q_o} = \frac{|S_{22}|^2}{Q_\ell} - \frac{1 - |S_{22}|^2}{n\pi} \quad (4.1)$$

where S_{22} is the reflection parameter of the test setup as seen from the resonator section at the gap and n is the order of the resonance. This is a good approximate formula, but it is not useful since S_{22} cannot be measured. In the case where the stripline has the same characteristic impedance as the network analyzer, the the unloaded Q can be estimated using

$$\frac{1}{Q_o} = \frac{1}{Q_\ell} [1 - |S_{21}|] \quad (4.2)$$

For the case in which the gap is large, the magnitude of S_{21} is approximately equal to zero and the loading effects can be considered to be negligible. For this case Q_o is approximately equal to Q_ℓ .

4.3 Experimental Verification

In order to verify this method experimentally, a series of stripline resonators was constructed using Rogers Duroid 5880 printed circuit boards. These boards were chosen because their loss parameters are already well characterized and they can be easily fashioned into striplines. These boards consist of a 62 mil thick teflon composite dielectric with a relative dielectric constant of 2.2. The loss tangent of this dielectric has been found to be 0.0009 at 10 GHz. This dielectric material is coated on both sides with 2 ounce copper which has a conductivity of 5.0×10^7 S/m. This copper is measured to be 2.34 mils thick using a profilometer. Using the computer simulation SRM, a series of resonators was designed to have parameters: $b=124$ mils, $t=2.34$ mils, $w=70, 85, 105, 120$ mils, $s=100$ mils, $L_1=400$ mils, $L_2=2000$ mils, $\epsilon_r=2.2$, $\sigma=5.0 \times 10^7$ S/m and $\tan\delta=0.0009$. The results of simulating these resonators with SRM are shown in table 4.1. The simulated response of the 120 mil wide resonator is shown in figure 4.1. The values of $\frac{1}{Q_\ell}$ are plotted versus $g(b,t,w)$ in figure 4.2.

Table 4.1: Values of f_r in GHz, $|S_{21}|$, Z_o in ohms, $g(b,t,w)$ in 1/cm, Q_ℓ ,
and Q_o for each of the resonator widths.

w	f_r	$ S_{21} $	Z_o	$g(b,t,w)$	Q_ℓ	Q_o
70	2.036	-39.42	60.44	11.36	361.09	364.88
85	2.036	-38.72	54.10	10.84	371.64	375.80
105	2.036	-38.03	47.46	10.31	383.54	388.09
120	2.036	-37.46	43.46	9.98	391.65	396.45

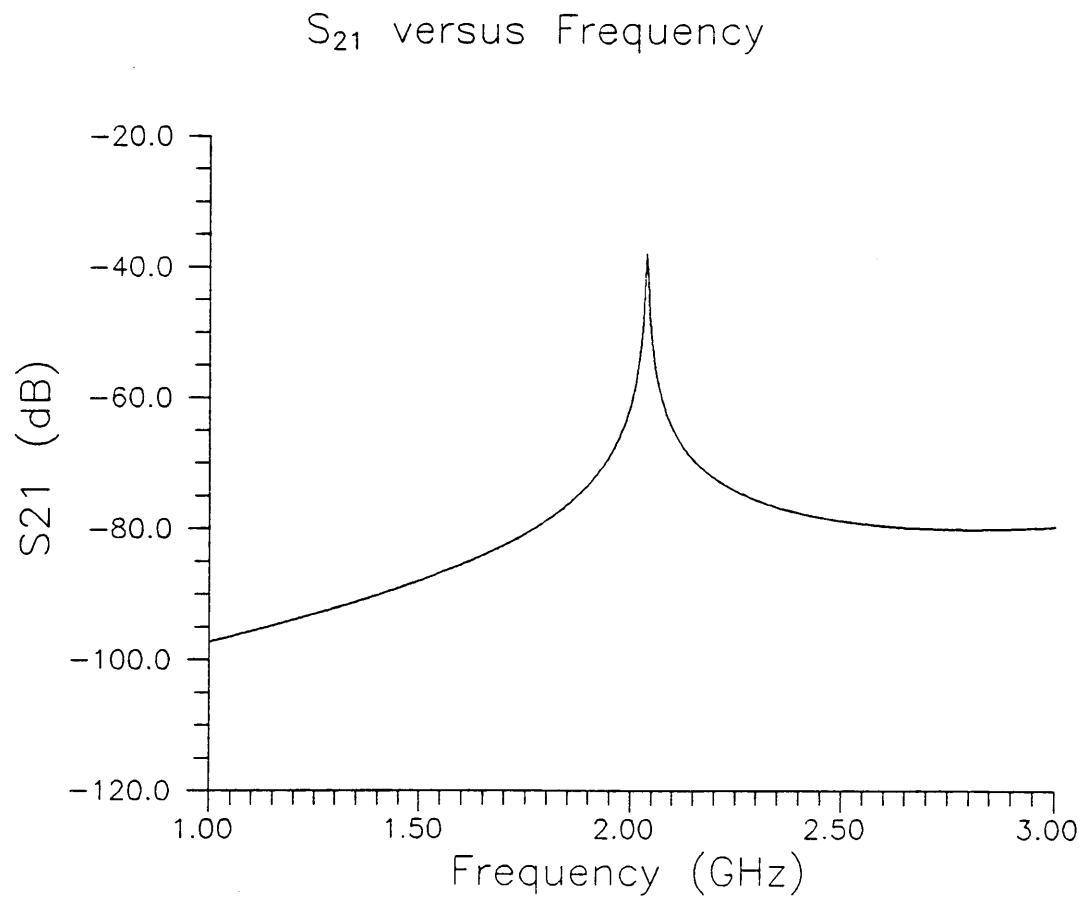


Figure 4.1: Plot of computer simulated |S₂₁| versus frequency for the
120 mil wide resonator.

$1/Q_0$ versus $g(b,t,w)$

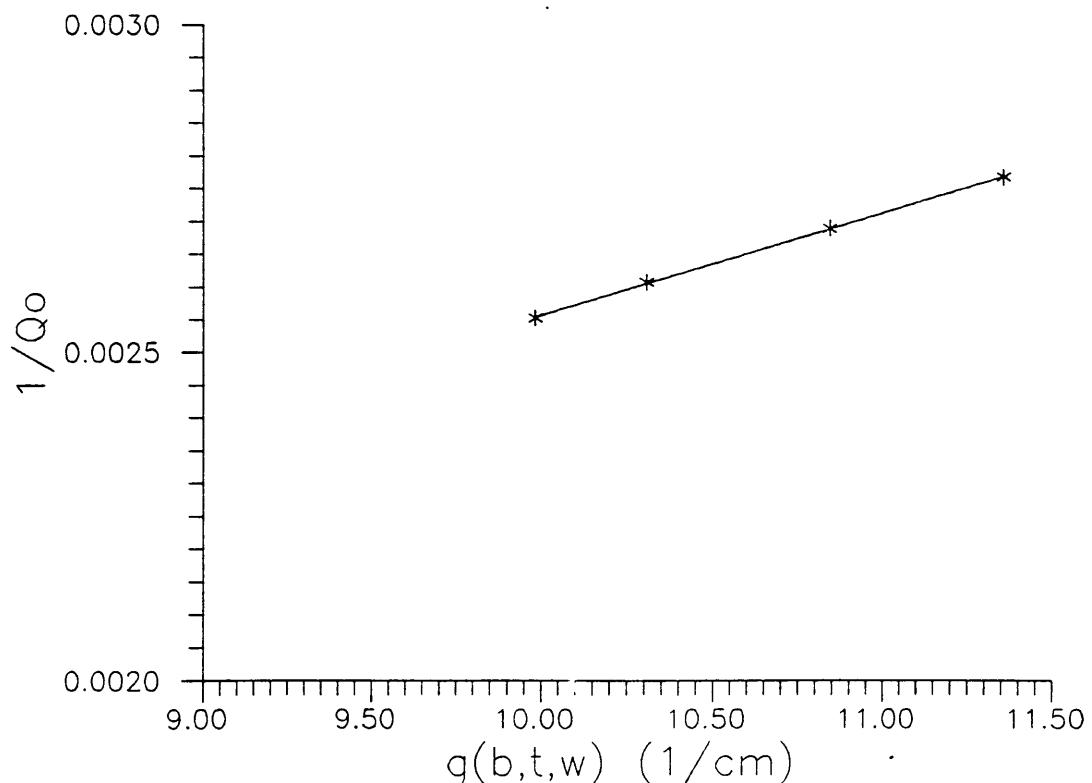


Figure 4.2: Plot of $\frac{1}{Q_\ell}$ versus $g(b,t,w)$ for the simulated experiment including a straight line fit to the data.

The line which is fit to the points in figure 4.2 corresponds to $\sigma=5.14\times 10^7$ S/m and $\tan\delta=0.00098$. These values correspond to a 2.8% error in predicting σ and a 8.8% error in predicting $\tan\delta$ relative to the original assumed values. This error is expected because of the assumption that the losses are small in relating the quality factor to the attenuation factor.

These boards were constructed using the methods outlined in appendix A. They were each measured on an HP8510 network analyzer. The results of these measurements are shown in table 4.2. The network analyzer output is plotted along with the simulated response for the 120 mil wide resonator in figure 4.3. The inverse quality factor is plotted versus $g(b,t,w)$ in figure 4.4. The line fit to this data corresponds to $\sigma=4.05\times 10^7$ S/m and $\tan\delta=0.000803$. The value of the conductivity is lower than the expected value for copper. This is due to surface roughness at the interface with the dielectric. The value of the loss tangent is close to the value specified by the manufacturer. The difference is probably due to the fact that the measurements were done at 2 GHz and the manufacturers specification is for 10 GHz. The frequency of the first resonance is 2.036 GHz which implies that $2.06 \leq \epsilon_r \leq 2.27$. This listed value of 2.2 falls in this range as expected. These results show that this method is feasible for characterizing the material properties of low loss printed circuit boards.

Table 4.2: Values of f_r in GHz, $|S_{21}|$, Z_o in ohms, $g(b,t,w)$ in 1/cm, Q_ℓ ,
and Q_o for each of the resonator widths.

w	f_r	$ S_{21} $	Z_o	$g(b,t,w)$	Q_ℓ
70	1.96	-44.75	60.44	11.36	355.63
85	1.96	-39.43	54.10	10.84	367.63
105	1.96	-36.75	47.46	10.31	381.28
120	1.96	-34.58	43.46	9.98	388.88

S_{21} versus Frequency

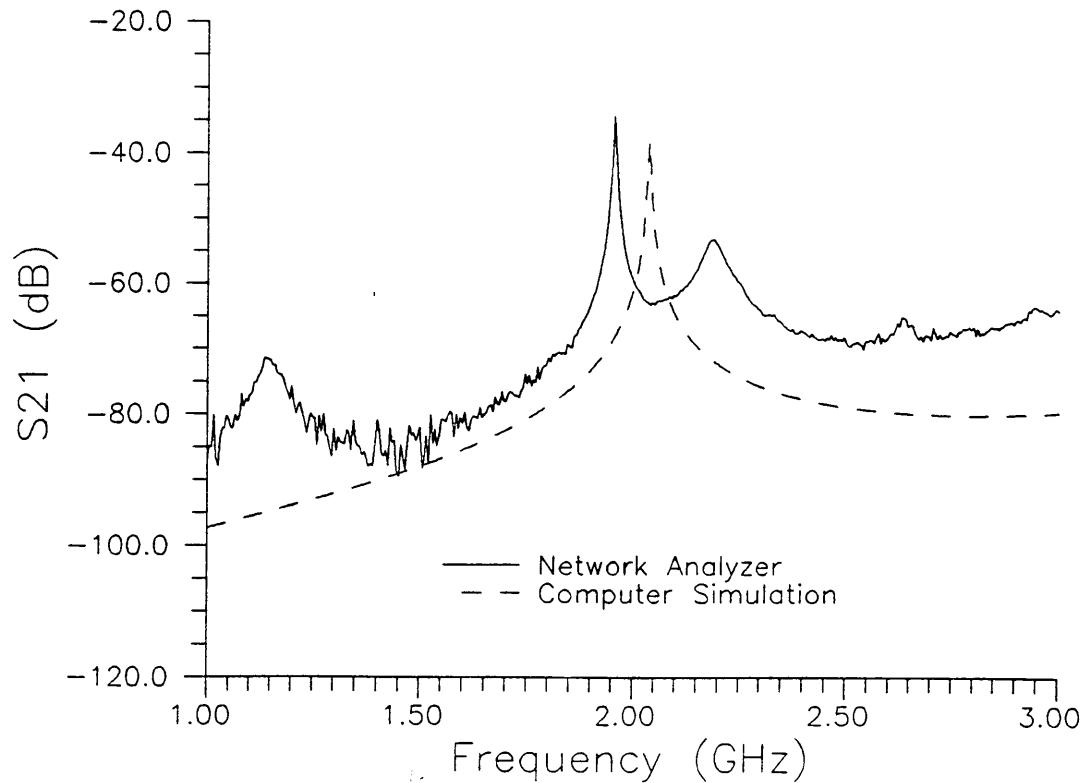


Figure 4.3: Plot of $|S_{21}|$ versus frequency from simulation and the HP8510 for the 120 mil wide resonator.

$1/Q_0$ versus $g(b,t,w)$

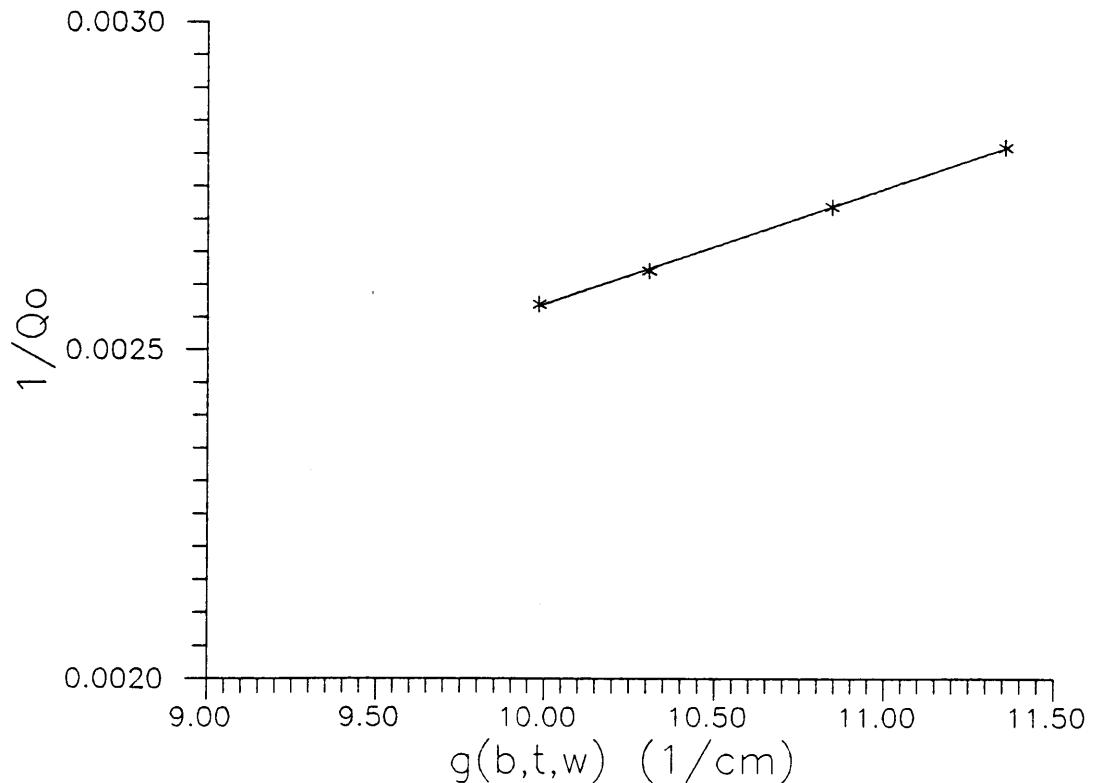


Figure 4.4: Plot of $\frac{1}{Q_\ell}$ versus $g(b,t,w)$ for the experiment
including a straight line fit to the data.

4.4 Summary

This chapter described a method for measuring stripline resonators constructed from printed circuit boards. The results of these measurements were analyzed using the SRM computer program. This analysis showed the material parameters to be similar to those given by the manufacturer for these printed circuit boards. This chapter also showed that the SRM computer program can be used to accurately predict the response of stripline resonators. These results show that this stripline resonator method is feasible for characterizing low loss materials which can be used to construct striplines.

Chapter 5

Summary and Conclusions

5.1 Summary

By constructing a series of stripline resonators, it is possible to characterize the materials from which the striplines are made. Chapter 2 describes a method which separates the loss terms based on the variation of loss with stripline dimensions. This method is advantageous because it produces accurate results, even if the material parameters vary with frequency. Chapter 2 also describes a method for finding the relative permittivity based on resonant frequency. Chapter 3 describes the theory for modelling a stripline resonator with s-parameters. This theory has been incorporated into a computer program called SRM which has been shown to be very useful for predicting the response of resonators during design and for analyzing experimental data. Chapter 3 includes a

simulated experimental design and an analysis of the sensitivity of the response of resonators to the design parameters. Chapter 4 covers the design and testing of a series of resonators to measure a printed circuit board material. The results of chapter 4 showed that the SRM program is an effective design tool and that this method can be used to measure the material parameters of low loss materials.

5.2 Conclusions

The stripline resonator method presented in this thesis has been shown to be an effective method for characterizing low loss printed circuit board materials. This method should be equally effective on any low loss material which can be used to create striplines and which has stable dimensions. This method may be useful for high loss materials if a better model can be developed which does not use low loss approximations to relate attenuation to quality factor. This technique may also be used for thick film materials, if the dimensions of the striplines are measured accurately using a profilometer. This technique combines the best features of transmission line and cavity techniques and produces very good results when applied properly.

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Appendix A

Processing Methods

A.1 Introduction

This appendix describes a method for producing, stripline resonators from copper clad printed circuit boards. This method is useful for producing striplines from most printed circuit boards which are clad on both sides with copper. The important parameters of these substrates are the dielectric constant, the dielectric loss tangent, the dielectric thickness and the conductor thickness.

A.2 Manufacturing Process

For each stripline, it is necessary to produce two boards. One board will have copper on the back side and the stripline etched on the front side. The second board will have copper on the back side and all the copper etched off of the front side. When these two boards are pressed together in the measurement phase, this will create a stripline with two copper ground planes. For the purpose of this paper, the board with the stripline etched on it will be referred to as the bottom board and the board with all the copper etched off of one side will be referred to as the top board.

These boards will be produced using photoresist and copper etchant to selectively etch a pattern on the substrate. Since there are many methods for producing and etching patterns, the specifics of the method used will only be provided here. References to alternate methods are provided for some procedures. In order to produce the bottom board, it is necessary to produce a positive of the pattern to be etched. The term positive here means a sheet of film which is transparent in the areas to be etched and opaque in the areas to be left with copper. This positive will be used to expose the pattern on the photoresist.

In order to produce the positive, a method common in producing screens for

printing thick film hybrid circuits is used. This method uses Rubylith films and a reduction camera. Rubylith is a clear film which is coated with a thin layer of red mylar. This mylar can be cut and peeled away in a pattern while leaving the clear film in tact. This leaves a high contrast pattern which can be placed on a light table and photographically reduced with a an interchangeable lens medium format camera. The full process is as follows:

- 1) Design of the pattern
- 2) Transfer the pattern to Rubylith
- 3) Photograph the Rubylith
- 4) Apply the photoresist to the boards
- 5) Expose and develop the photoresist
- 6) Etch the boards

A.2.1 Design of the Pattern

To design the pattern, the ©MicroCad package is used. This package was designed specifically for making this type of pattern. The program works with a user specified substrate size and uses dimensions in mils. The program supports the use of multiple layers, but this design does not require the use of that capability. Patterns for 3 inch X 3 inch substrates are created. A sample of this type of pattern is shown in Figure A.1. A 60 mil X 60 mil box is placed in each corner to use as alignment markers. These will leave a little copper on the corner of the substrate, but this is negligible and can be filed off later.

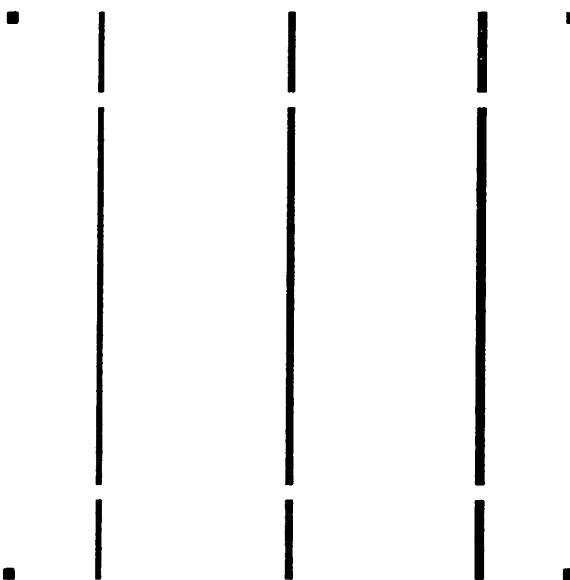


Figure A.1: Typical stripline pattern for a 3" X 3" substrate.

A.2.2 Pattern Transfer to Rubylith

To gain good resolution in the final positive, a 10:1 reduction from the rubylith to the film is used. This means that the pattern needed to be plotted on a 30 inch X 30 inch piece of Rubylith. This can be achieved by one of three methods. If a large bed plotter with an adjustable pen pressure is available, then the plotter can cut the Rubylith automatically with a diamond tipped scribe. This is the preferred method because it produces the most accurate results and requires very little effort. For a plotter without adjustable pen pressure, the pattern should be plotted on a large sheet of paper and carefully hand cut into the Rubylith on a light table. It is advisable to use a metal straight edge to guide the knife when cutting in order obtain accurate results. If a plotter is not available, then the design can be hand drawn on graph paper and then cut.

A.2.3 Photographing the Rubylith

After cutting, the Rubylith was placed on a green surfaced light table at a distance of about 6 feet from the camera. Back illumination provides good contrast and eliminates surface reflections. The green surface produces good contrast with the red film on the Rubylith. The camera used is a 4 inch X 5 inch bellows camera.

For 10:1 reduction, a 5.6/150 (minimum *f*-stop / focal length) lens produced by Schneider-Kreuznach is used. I set the aperture at f32 with the bellows fully extended. This camera has a removable backing plate which loads single sheets of film. The backing plate is attached to a vacuum pump which holds the film flat in a vertical position on the backing plate.

The film used is Kodak Kodalith Ortho Film (type 3). To make a positive, a piece of film is placed in the camera with the emulsion side (lighter colored side or dull side) towards the lens and exposed with the light table lights for 30 seconds. This film is developed in two part Kodalith Developer (mixed 1:1) until the corners of the print turn dark black. The corners tend to get less exposure due to uneven light table illumination. After developing, the film is placed in stop bath for 30 seconds and in fixer for 5 minutes. It should then be washed for 10 minutes and hung to dry in a dust free environment.

A.2.4 Applying the Photoresist

Applying the photoresist is the most difficult step in the process. This is because uneven spreading of the layer and contamination can produce serious results. The first step is to be sure that the substrates are clean and free of oxide layers. Acetone and a lint free cloth are used to clean the substrates. For tough oxide layers, the surface can be rubbed lightly with steel wool. It is also very important

that the substrates be flat. Once the substrates are clean, the photoresist is applied by spinning onto one side of one of the two substrates. This is the side which will have the exposed pattern. The other substrate is left alone at this time because we want to etch one side of it clean. After drying, photoresist will be applied to the back side of both of these substrates.

The photoresist is applied using a vacuum spinner produced by Headway Research. This spinner has a small head about 0.75 inches in diameter with a rubber gasket and a vacuum feed. The gasket should make a tight seal with the bottom of the substrate which allows the vacuum to hold it in place. To get a good seal, it is necessary to have a flat substrate and a clean spinner head. The spinner head is cleaned with acetone and a lint free cloth. The photoresist used is ©Microdeposit 1400-27 by Shipley. To spin a substrate, place it on the head and check the vacuum seal by dry spinning it with no photoresist. This is important because if the photoresist is applied and the seal is not good, the spinner will throw the substrate and the photoresist off the spinner head. After dry spinning, use an eyedropper to place photoresist over the entire top surface of the substrate. This process wastes a bit of photoresist, but insures a level coating. After coating, place a splash shield around the spinner and spin the substrate for 20 seconds at 2500 RPM. After spinning, place the substrate on an oven tray for drying. Dry the substrate in an oven for 20 minutes at 90°C. This will dry and harden the photoresist.

After drying, let the substrate cool for about 15 minutes. Now the photoresist needs to be applied to the back side of both the top and bottom pieces. It is not possible to use the spinner to achieve this task, because the spinner head would damage the photoresist layer which was applied earlier. Since these sides will not have a pattern printed on them, an even layer of photoresist is not necessary. This layer is meant to stop all etching so it should be thick which makes it more durable under agitation. To spread this thick layer, both substrates are layed on a lint free cloth with the side to be coated facing up. The eyedropper is used to place some photoresist to the substrates and then it is spread over the substrate with a small piece of paper. This produces a thicker layer than spinning. The substrates are dried in the oven for 40 minutes at 90°C. After drying, the substrates are ready to have the pattern exposed.

A.2.5 Exposing and Developing the Pattern

To expose the pattern, the substrate is placed on a large piece of glass. The positive is then placed on top of the substrate with the emulsion side away from the substrate. The positive should be placed in the proper alignment and covered with a piece of very clean glass. The resulting sandwich should be clamped together using some type of low pressure clamp. To expose the photoresist, an ultraviolet exposure system by HLC Manufacturing Company is used. This unit has a 1000 watt ultraviolet illuminator. The substrates are placed under the lens

and an 8 second exposure is made.

The substrates are developed in a small tray with ©Microdeposit Developer 353 by Shipley. While developing, the substrate will appear to give off red streaks into the developer. As soon as these streaks stop, the substrate should be removed and washed with water for 3 minutes. Over developing can degrade the quality of the pattern. After washing, the substrate is dried for 20 minutes at 100°C.

A.2.6 Etching the Substrates

The substrates are etched using a solution of 39.00% FeCl_3 and 61.00% H_2O . The substrate should be placed in a small tray and covered with about a quarter inch of etchant. The tray should be agitated gently; violent agitation may scrape the photoresist off of the back side. The etchant should be changed when it becomes a dark black color and fails to etch sufficiently. After the etching is complete, the substrate should be washed with water for 3 minutes. The photoresist can then be washed off using acetone. The substrates should be given a final wash in water. The substrates are now completed and ready to be cut and clamped into striplines.

A.3 Special Technique for Thin Substrates

For thin substrates (thickness less than 10 mils) special spinning techniques are necessary because the substrates are not rigid enough for normal spinning methods. This is because the spinner vacuum will create a deformation in the center of the substrate and because the substrate will sag at the corners and produce an uneven layer. A solution to this problem is to attach the substrate to a base of flat rigid material. Suitable materials include a thin piece of plexiglass or a thin alumina substrate. If the substrate has protective plastic coating, two-sided tape can be used to attach the substrate to the base. If there is no plastic coating, this method cannot be used because the residue from the adhesive will prevent proper photoresist adhesion. An alternative is to use a base which is slightly larger than the substrate and to tape the corners of the substrate to the base. This will leave small areas in each corner with no photoresist. This is not a problem if these areas are not part of the stripline pattern, since these areas are to be etched clean of copper and do not need photoresist masking.

Appendix B

SRM Computer Program

B.1 Introduction

This appendix describes a computer program, written by the author, called SRM.

This program uses the method described in chapter 3 to model stripline resonators and predict their response. This program can also be used to analyze experimental data by calculating values of $g(b,t,w)$. This program can also be used to do sensitivity analysis. This appendix includes a description of each of the programs four functions and a listing of the FORTRAN source code.

B.2 SRM Program Functions

The program SRM has four functions which can be selected from a menu after running the program. These functions are:

- 1) Run a series of resonators.
- 2) Run individual resonators.
- 3) Analyze experimental data.
- 4) Sensitivity data.

Function 1 is used to simulate a series of resonators with varying widths. This function produces three types of output files. The first is a comprehensive data file which summarizes the input parameters and the computed results. The second is a data file which can be used to plot the inverse unloaded quality factor versus $g(b,t,w)$ for the series of resonators. The third is a file for each resonator which can be used to plot $|S_{21}|$ versus frequency for that resonator.

Function 2 is almost the same as function 1, except that it allows variation of all of the resonator parameters and does not produce a file to plot inverse quality factor versus $g(b,t,w)$. This function is useful when varying input parameters in order to obtain a desired output response.

Function 3 is used to analyze results of experiments. It accepts a series of resonator parameters, quality factors, and resonant frequencies as input and produces an output file containing data for a plot of inverse quality factor versus $g(b,t,w)$.

Function 4 produces plots of the variation of $g(b,t,w)$ and Z_o versus b , t , and w . These plots can be used to study the sensitivity of these parameters as demonstrated in chapter 3.

B.3 SRM Program Functions

The SRM program is written in double precision and was compiled using ©Microsoft Fortran. A listing of the program follows. This listing is well documented and should be easily understood.

```
C*****
C      main program - by Mark A. Busse
C
      real*8 fff(1600),sss(1600)
      integer*4 i,j,k,l,m,n
      write(6,*)' 1 - Run a series of resonator widths'
      write(6,*)' 2 - Run individual resonators'
      write(6,*)' 3 - Analyze experimental data'
      write(6,*)' 4 - Sensitivity plots against b, t, and w'
      write(6,*)
      write(6,*)' Which function ? '
      read(5,*)
      if(i.eq.1) call fun1(fff,sss)
```

```

if(i.eq.2) call fun2(fff,sss)
if(i.eq.3) call fun3
if(i.eq.4) call fun4
end

c
c  end of main program
c
C*****subroutine c_qo
c
subroutine c_qo(f1,fh,bstep,lstep,er,sigma,tand,gbtw,b,s,l1,l2
1,zt,z0,q,ql,qt,smax,fmax)
complex*16 z0,yo,zt,za,zb,y1,y2,y3,gam
real*8 b,t,w,s,l1,l2,lam,lamg,f,er,cv,dp0,pi,xa,xb,zot
real*8 gbtw,qc,iqc,q,iq,ql,iql,alpha,beta,vp
real*8 f1,fh,s21,s1,s2,s3,f1,f2,f3,fstep,fmax,smax,smax2
real*8 f1b,fhb,smaxl1,smaxm,qt,sigma,tand,wa(20)
real*8 bstep,lstep,nx
integer*4 imax,nl,i,j,k,l,m,n,nwa,np,imx
complex*16 ss(2,2)

c
c  initialize
c
pi=3.14159265358979
dp0=0.0
cv=0.00254
zt=dcmplx(dble(50.0),dble(0.0))

c
j=0
c
c  step through frequency to accurately determine fmax
c
do 11 f=f1,fh,lstep
j=j+1
nl=0
call com_s(f,er,sigma,tand,gbtw, nl,b,s,l1,l2,zt,z0,ss,qt)
s1=s2
f1=f2
s2=s3
f2=f3
s3=dble(20.0)*dlog10(cdabs(ss(2,1)))
f3=f

c
if(j.lt.3) go to 11
if(s2.gt.s1.and.s2.gt.s3) then

```

```

fmax=f2
write(6,*)" fmax ",fmax
go to 12
endif
c
11 continue
c
c   find the s-parameters at fmax
c
12 nl=0
call com_s(fmax,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
smax=dble(20.0)*dlog10(cdabs(ss(2,1)))
write(6,*)smax
smaxm=cdabs(ss(2,1))
write(6,*)" Q original ",qt
c
c   find the s-paramters of the launching area looking from the
c   strip
c
nl=0
call com_s2(fmax,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
write(6,*)cdabs(ss(1,1)),cdabs(ss(2,2))
smax2=cdabs(ss(1,1))
nl=1
call com_s(fmax,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
smaxnl=dble(20.0)*dlog10(cdabs(ss(2,1)))
c
c   find the left 3 dB point
c
f=fmax
20 f=f-bstep
nl=0
call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
if(dble(20.0)*dlog10(cdabs(ss(2,1))).ge.smax-dble(3.0)) go to 20
f=f-lstep
21 f=f+lstep
nl=0
call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
if(dble(20.0)*dlog10(cdabs(ss(2,1))).lt.smax-dble(3.0)) go to 21
flb=f
c
c   find the right 3 dB point
c
f=fmax
30 f=f+bstep
nl=0

```

```

call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
if(dble(20.0)*dlog10(cdabs(ss(2,1))).ge.smax-dble(3.0)) go to 30
f=f+lstep
31 f=f-lstep
nl=0
call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
if(dble(20.0)*dlog10(cdabs(ss(2,1))).lt.smax-dble(3.0)) go to 31
fhb=f

c
c  find the unloaded quality factor
c
write(6,*)flb,fmax,fhb
ql=fmax/(fhb-flb)
write(6,*)" ql = ",ql
write(6,*)smax,smaxnl,smaxm
nx=(dble(2.0)*fmax*sqrt(er)*(l2+s))/dble(3.0e10)
write(6,*)" nx = ",nx
iq=(1.0/ql)*(smax2*smax2)-(dble(1.0)-(smax2*smax2))/(nx*pi)
q=1.0/iq
write(6,*)" Est. uni. Q ",dble(1.0)/((1.0/ql)*(1-smaxm*smaxm))
write(6,*)" Unloaded Q ",gbtw,q
110 format(1x,f10.5,5x,f15.10)
c
return
end
c
c  end of subroutine c_qo
c
*****
c
c  subroutine fun1
c
subroutine fun1(fff,sss)
complex*16 zo,yo,zt,za,zb,y1,y2,y3,gam
real*8 b,t,w,s,l1,l2,lam,lamg,f,er,cv,dp0,pi,xa,xb,zot
real*8 gbtw,g1btw,qc,iqc,q,iq,ql,iql,alpha,beta,vp
real*8 max(20),fl,fh,s21,s1,s2,s3,f1,f2,f3,fstep,fmax,smax
real*8 flb,fhb,smaxnl,smaxm,qt,sigma,tand,wa(20)
real*8 flp,fhp,pstep,bstep,lstep
integer*4 imax,ni,i,j,k,l,m,n,nwa,np,imx
complex*16 ss(2,2)
character*30 file1,file2(20),file3
real*8 fff(1600),sss(1600)

c
c  initialize
c

```

```

pi=3.14159265358979
dp0=0.0
cv=0.00254
zt=dcmplx(dble(50.0),dble(0.0))
bstep=0.001e9
lstep=0.00001e9
imx=0
c
c   read the name of the comprehensive file name
c
write(6,*)' Input the name of the comprehensive file ? '
read(5,130)file1
130 format(a30)
open(unit=1,file=file1,status='new')
c
write(6,*)' Input the name of the plot data file ? '
read(5,130)file3
open(unit=3,file=file3,status='new')
c
c   read in the parameters
c
write(6,*)' Input the b dimension ? '
read(5,*)b
b=b*cv
write(6,*)' Input the t dimension ? '
read(5,*)t
t=t*cv
write(6,*)' Input the l1 dimension ? '
read(5,*)l1
l1=l1*cv
write(6,*)' Input the l2 dimension ? '
read(5,*)l2
l2=l2*cv
write(6,*)' Input the s dimension ? '
read(5,*)s
s=s*cv
write(6,*)' Input the epsilon relative ? '
read(5,*)er
write(6,*)' Input the sigma ? '
read(5,*)sigma
write(6,*)' Input the tan delta ? '
read(5,*)tand
write(6,*)' Input the flp ? '
read(5,*)flp
flp=flp*dble(1.0e9)
write(6,*)' Input the fhp ? '

```

```

read(5,*)fhp
fhp=fhp*dble(1.0e9)
pstep=(fhp-flp)/dble(500.0)
write(6,*)" Input the number of widths ? "
read(5,*)nwa
c
c  read in the widths
c
do 60 i=1,nwa
write(6,*)" Input width number ',i,' ? "
read(5,*)wa(i)
write(6,*)" Input the name of width file',wa(i),' ? "
read(5,130)file2(i)
60 continue
c
c  step through the widths
c
do 50 k=1,nwa
np=0
w=wa(k)*cv
open(unit=2,file=file2(k),status='new')
c
c  compute the characteristic impedance
c
call compute_zo(b,t,w,er,zot)
zo=dcmplx(zot,dble(0.0))
c
c  compute g(b,t,w)
c
call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
c  find the points for the plot and the approximate locations of
c  the maxima
c
j=0
imax=0
do 10 f=flp,fhp,pstep
j=j+1
nl=0
call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
s1==s2
f1=f2
s2==s3
f2=f3
s3=dble(20.0)*dlog10(cdabs(ss(2,1)))
f3=f

```

```

c
np=np+1
fff(np)=f3
sss(np)=s3
c
if(j.lt.3) go to 10
if(s2.gt.s1.and.s2.gt.s3) then
imax=imax+1
max(imax)=f2
write(6,100)imax,max(imax),s2
100 format(1x,'Max. # ',i3,' at ',g12.6,' s21 = ',f10.5)
endif
c
10 continue
c
c   write the data points to the file
c
write(6,*)' np = ',np
do 70 i=1,np
write(2,120)fff(i)/dble(1.0e9),sss(i)
70 continue
120 format(1x,f12.6,f12.6)
c
close(unit=2)
c
write(6,*)' Pick a maximum ? '
read(5,*)imx
16 fl=max(imx)-(dble(1.0)*pstep)
fh=max(imx)+(dble(1.0)*pstep)
c
c   calculate the unloaded quality factor
c
call c_qo(fl,fh,bstep,lstep,er,sigma,tand,gbtw,b,s,l1,l2
1,zt,zo,q,ql,qt,smax,fmax)
c
write(3,*)gbtw,dble(1.0)/ql,dble(1.0)/q
write(1,*)' File = ',file2(k)
write(1,*)' b = ',b/cv
write(1,*)' t = ',t/cv
write(1,*)' w = ',wa(k)
write(1,*)' s = ',s/cv
write(1,*)' l1 = ',l1/cv
write(1,*)' l2 = ',l2/cv
write(1,*)' er = ',er
write(1,*)' sigma = ',sigma
write(1,*)' tand = ',tand

```

```

write(1,*)' fmax = ',fmax
write(1,*)' smax = ',smax
write(1,*)' Zo = ',dreal(zo)
write(1,*)' g(b,t,w) = ',gbtw
write(1,*)' q org = ',qt
write(1,*)' q loaded = ',ql
write(1,*)' q unloaded = ',q
50 continue
close(unit=1)
return
end
c
c end of subroutine fun1
c
C*****
c
c subroutine fun2
c
c subroutine fun2(fff,sss)
c
complex*16 zo,yo,zt,za,zb,y1,y2,y3,gam,gamc
real*8 b,t,w,s,l1,l2,lam,lamg,f,er,cv,dp0,pi,xa,xb,zot
real*8 gbtw,g1btw,qc,iqc,q,iq,ql,iql,alpha,beta,vp
real*8 max(20),fl,fh,s21,s1,s2,s3,f1,f2,f3,fstep,fmax,smax
real*8 ffb,fhb,smaxnl,smaxm,qt,sigma,tand,wa(20)
real*8 flp,fhp,pstep,bstep,lstep,ttt,ca
integer*4 imax,nl,i,j,k,l,m,n,nwa,np,imx
complex*16 ss(2,2)
character*30 file1,file2
real*8 fff(1600),sss(1600)
c
c initialize
c
pi=3.14159265358979
dp0=0.0
cv=0.00254
zt=dcmplx(dble(50.0),dble(0.0))
bstep=0.001e9
lstep=0.00001e9
c
c read the name of the comprehensive file
c
write(6,*)' Input the comprehensive file name ? '
read(5,110)file1
open(unit=1,file=file1,status='new')

```

```

c
c   read the name of the data file
c
50 imx=0
    write(6,*)' Input the file name ? '
    read(5,110)file2
110 format(a30)
    open(unit=2,file=file2,status='new')
c
c   read in the parameters
c
    write(6,*)' Input the b dimension ? ',b/cv
    read(5,*)ttt
    if(ttt.ne.0.0)b=ttt*c
c
    write(6,*)' Input the t dimension ? ',t/cv
    read(5,*)ttt
    if(ttt.ne.0.0)t=ttt*c
c
    write(6,*)' Input the w dimension ? ',w/cv
    read(5,*)ttt
    if(ttt.ne.0.0)w=ttt*c
c
    write(6,*)' Input the l1 dimension ? ',l1/cv
    read(5,*)ttt
    if(ttt.ne.0.0)l1=ttt*c
c
    write(6,*)' Input the l2 dimension ? ',l2/cv
    read(5,*)ttt
    if(ttt.ne.0.0)l2=ttt*c
c
    write(6,*)' Input the s dimension ? ',s/cv
    read(5,*)ttt
    if(ttt.ne.0.0)s=ttt*c
c
    write(6,*)' Input the epsilon relative ? ',er
    read(5,*)ttt
    if(ttt.ne.0.0)er=ttt
c
    write(6,*)' Input the sigma ? ',sigma
    read(5,*)ttt
    if(ttt.ne.0.0)sigma=ttt
c
    write(6,*)' Input the tan delta ? ',tand
    read(5,*)ttt
    if(ttt.ne.0.0)tand=ttt

```

```

c
write(6,*)" Input the flp ? ",flp
read(5,*)ttt
if(ttt.ne.0.0)flp=ttt*dble(1.0e9)
c
write(6,*)" Input the fhp ? ",fhp
read(5,*)ttt
if(ttt.ne.0.0)fhp=ttt*dble(1.0e9)
pstep=(fhp-flp)/dble(500.0)
c
open(unit=2,file=file2,status='new')
c
c compute the characteristic impedance
c
call compute_zo(b,t,w,er,zot)
zo=dcmplx(zot,dble(0.0))
c
c compute g(b,t,w)
c
call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
c find the points for the plot and the approximate locations of
c the maxima
c
np=0
j=0
imax=0
do 10 f=flp,fhp,pstep
j=j+1
nl=0
call com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,qt)
s1=s2
f1=f2
s2=s3
f2=f3
s3=dble(20.0)*dlog10(cdabs(ss(2,1)))
f3=f
c
np=np+1
fff(np)=f3
sss(np)=s3
c
if(j.lt.3) go to 10
if(s2.gt.s1.and.s2.gt.s3) then
imax=imax+1
max(imax)=f2

```

```

      write(6,100)imax,max(imax),s2
100 format(1x,'Max. # ',i3,' at ',g12.6,' s21 = ',f10.5)
      endif
c
10 continue
c
      write(6,*)' np = ',np
c
j=0
      write(6,*)' Pick a maximum ? '
      read(5,*)imx
16 fl=max(imx)-(dble(1.0)*pstep)
      fh=max(imx)+(dble(1.0)*pstep)
c
c  compute the unloaded quality factor
c
      call c_qo(fl,fh,bstep,lstep,er,sigma,tand,gbtw,b,s,l1,l2
     1,zt,zo,q,ql,qt,smax,fmax)
c
c  write the data to the comprehensive file
c
      write(1,*)' File = ',file2
      write(1,*)' b = ',b/cv
      write(1,*)' t = ',t/cv
      write(1,*)' w = ',w/cv
      write(1,*)' s = ',s/cv
      write(1,*)' l1 = ',l1/cv
      write(1,*)' l2 = ',l2/cv
      write(1,*)' er = ',er
      write(1,*)' sigma = ',sigma
      write(1,*)' tand = ',tand
      write(1,*)' fmax = ',fmax
      write(1,*)' smax = ',smax
      write(1,*)' Zo = ',dreal(zo)
      write(1,*)' g(b,t,w) = ',gbtw
      write(1,*)' q org = ',qt
      write(1,*)' q loaded = ',ql
      write(1,*)' q unloaded = ',q
c
c  write the data file
c
      do 70 i=1,np
      write(2,120)fff(i)/dble(1.0e9),sss(i)
70 continue
120 format(1x,f12.6,f12.6)
c

```

```

close(unit=2)
c
write(6,*)' Continue ? '
read(5,*)
if(l.eq.1) go to 50
close(unit=1)
return
end
c
c end of subroutine fun2
c
***** ****
c
c subroutine fun3
c
complex*16 zo,yo,zt,za,zb,y1,y2,y3,gam
real*8 b,t,w,s,l1,l2,lam,lamg,f,er,cv,dp0,pi,xa,xb,zot
real*8 gbtw,g1btw,qc,iqc,q,iq,ql,iql,alpha,beta,vp
real*8 max(20),f1,fh,s21,s1,s2,s3,f1,f2,f3,fstep,fmax,smax
real*8 f1b,fhb,smaxni,smaxm,qt,sigma,tand,wa(20)
real*8 f1p,fhp,pstep,ttt
integer*4 imax,nl,i,j,k,l,m,n,nwa,np,imx
complex*16 ss(2,2)
character*30 file1,file2
c
c initialize
c
pi=3.14159265358979
dp0=0.0
cv=0.00254
zt=dcmplx(dble(50.0),dble(0.0))
c
c read the name of the comprehensive file
c
write(6,*)' Input the comprehensive file name ? '
read(5,110)file1
open(unit=1,file=file1,status='new')

c
c read in the parameters
c
110 format(a30)
c
50 write(6,*)' Input the b dimension ? ',b/cv
read(5,*)ttt

```

```

if(ttt.ne.0.0)b=ttt*c
c
write(6,*)" Input the t dimension ? ',t/c
read(5,*)ttt
if(ttt.ne.0.0)t=ttt*c
c
write(6,*)" Input the w dimension ? ',w/c
read(5,*)ttt
if(ttt.ne.0.0)w=ttt*c
c
write(6,*)" Input the epsilon relative ? ',er
read(5,*)ttt
if(ttt.ne.0.0)er=ttt
c
write(6,*)" Input the maximum s21 ? ',smax
read(5,*)ttt
if(ttt.ne.0.0)smax=ttt
c
write(6,*)" Input the Q loaded ? ',ql
read(5,*)ttt
if(ttt.ne.0.0)ql=ttt
c
c compute the characteristic impedance
c
call compute_zo(b,t,w,er,zot)
c
c compute g(b,t,w)
c
call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
smaxm=dble(10.0)**(smax/dble(20.0))
if(ql.ne.0.0) iq=(dble(1.0)/ql)*(dble(1.0)-(smaxm*smaxm))
c
write(1,131)gbtw,iq,zot,b/cv,t/cv,w/cv
131 format(f9.3,1x,f11.9,1x,f9.3,1x,f10.5,1x,f10.5,1x,f10.5)
c
write(6,*)" Continue ? '
read(5,*)l
if(l.eq.1) go to 50
close(unit=1)
return
end
c
c end of subroutine fun3
c
*****

```

```

c
c subroutine fun4
c
c subroutine fun4
complex*16 zo,yo,zt,za,zb,y1,y2,y3,gam
real*8 b,t,w,s,l1,l2,lam,lamg,f,er,cv,dp0,pi,xa,xb,zot
real*8 gbtw,g1btw,qc,iqc,q,iq,ql,iql,alpha,beta,vp
real*8 max(20),f1,fh,s21,s1,s2,s3,f1,f2,f3,fstep,fmax,smax
real*8 fib,fhb,smaxnl,smaxm,qt,sigma,tand,wa(20)
real*8 ffp,fhp,pstep,ttt
integer*4 imax,nl,i,j,k,l,m,n,nwa,np,imx,isen
complex*16 ss(2,2)
character*30 file1,file2
c
c initialize
c
pi=3.14159265358979
dp0=0.0
cv=0.00254
zt=dcmplx(dble(50.0),dble(0.0))
c
write(6,*)" Input the comprehensive file name ? "
read(5,110)file1
open(unit=1,file=file1,status='new')
c
write(6,*)" Sensitivity of which variable ? "
read(5,*)isen
c
c read in the parameters
c
110 format(a30)
c
50 write(6,*)" Input the b dimension ? ",b/cv
read(5,*)ttt
if(ttt.ne.0.0)b=ttt*cv
c
write(6,*)" Input the t dimension ? ",t/cv
read(5,*)ttt
if(ttt.ne.0.0)t=ttt*cv
c
write(6,*)" Input the w dimension ? ",w/cv
read(5,*)ttt
if(ttt.ne.0.0)w=ttt*cv
c
write(6,*)" Input the epsilon relative ? ",er
read(5,*)ttt

```

```

        if(ttt.ne.0.0)er=ttt
c
        if(isen.eq.1) then
          do 10 ttt=10.0,200.0,0.5
            b=ttt*cv
c
c      compute the characteristic impedance
c
        call compute_zo(b,t,w,er,zot)
c
c      compute g(b,t,w)
c
        call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
c
        write(1,131)gbtw,g1btw,zot,b/cv,t/cv,w/cv
10 continue
        endif
c
        if(isen.eq.2) then
          do 20 ttt=0.1,2.5,0.01
            t=ttt*cv
c
c      compute the characteristic impedance
c
        call compute_zo(b,t,w,er,zot)
c
c      compute g(b,t,w)
c
        call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
c
        write(1,131)gbtw,g1btw,zot,b/cv,t/cv,w/cv
20 continue
        endif
c
        if(isen.eq.3) then
          do 30 ttt=10.0,50.0,0.1
            w=ttt*cv
c
c      compute the characteristic impedance
c
        call compute_zo(b,t,w,er,zot)
c
c      compute g(b,t,w)
c

```

```

call c_gbtw(b,t,w,zot,er,gbtw,g1btw)
c
c
write(1,131)gbtw,g1btw,zot,b/cv,t/cv,w/cv
30 continue
endif
c
close(unit=1)
131 format(f9.3,1x,f9.3,1x,f9.3,1x,f10.5,1x,f10.5,1x,f10.5)
return
end
c
c end of subroutine fun4
c
*****subroutine com_s*****
c
c subroutine com_s(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,q)
c
complex*16 zo,yo,zt,ya,yb,y1,y2,y3,gam,gamc
real*8 b,t,w,s,l1,l2,iam,iamg,f,er,cv,dp0,pi,ba,bb,zot
real*8 gbtw,qc,iqc,q,iq,alpha,beta,vp,sigma,tand,ca
complex*16 s1(2,2),s2(2,2),s3(2,2),s4(2,2),s5(2,2),s6(2,2),s7(2,2)
complex*16 t1(2,2),t2(2,2),t3(2,2),t4(2,2),t5(2,2),t6(2,2),t7(2,2)
complex*16 tt(2,2),ss(2,2),ts(2,2),st(2,2)
integer*4 nl
c
c initialize and find the line parameters
c
pi=3.14159265358979
iamg=(3.0e10)/(dsqrt(er)*f)
vp=(3.0e10)/dsqrt(er)
iqc=(1.5911/dsqrt(sigma*(f/1.0e9)))*gbtw
iq=iqc+tand
q=dble(1.0)/iq
c
if(nl.eq.1) then
alpha=dble(0.0)
else
alpha=pi/(q*iamg)
endif
beta=(2.0*pi)/iamg
gam=dcmplx(alpha,beta)
yo=dble(1.0)/zo
c

```

```

c  find the admittances of the equivalent gap circuit
c
c      call gap_circuit(s,b,zo,lambda,ba,bb)
c      ya=dcmplx(dp0,ba)
c      yb=dcmplx(dp0,bb)
c      y1=ya
c      y2=y1
c      y3=yb
c
c  find the s-parameters of each element
c
c      call s_disc(zt,zo,s1)
c      call s_line(zo,zo,gam,l1+(s/2.0),s2)
c      call s_line(zo,zo,gam,l1,s2)
c      call s_pi(yo,y1,y2,y3,s3)
c      call s_line(zo,zo,gam,l2+s,s4)
c      call s_line(zo,zo,gam,l2,s4)
c      call s_pi(yo,y1,y2,y3,s5)
c      call s_line(zo,zo,gam,l1+(s/2.0),s6)
c      call s_line(zo,zo,gam,l1,s6)
c      call s_disc(zo,zt,s7)
c
c  convert the s-parameters to t-parameters
c
c      call con_t(s1,t1)
c      call con_t(s2,t2)
c      call con_t(s3,t3)
c      call con_t(s4,t4)
c      call con_t(s5,t5)
c      call con_t(s6,t6)
c      call con_t(s7,t7)
c
c  multipliy the matrices
c
c      call m_m(t1,t2,tt)
c      call m_m(tt,t3,ts)
c      call m_m(ts,t4,tt)
c      call m_m(tt,t5,ts)
c      call m_m(ts,t6,tt)
c      call m_m(tt,t7,ts)
c
c  convert back to s-parameters
c
c      call con_s(ts,ss)
c      write(6,*)f,10.0*dlog10(cdabs(ss(2,1)))
c

```

```

    return
end

c
c  end of subroutine com_s
c
c***** ****
c
c subroutine com_s2
c
subroutine com_s2(f,er,sigma,tand,gbtw,nl,b,s,l1,l2,zt,zo,ss,q)
c
complex*16 zo,yo,zt,ya,yb,y1,y2,y3,gam,gamc
real*8 b,t,w,s,l1,l2,lamg,f,er,cv,dp0,pi,ba,bb,zot
real*8 gbtw,qc,iqc,q,iq,alpha,beta,vp,sigma,tand,ca
complex*16 s1(2,2),s2(2,2),s3(2,2),s4(2,2),s5(2,2),s6(2,2),s7(2,2)
complex*16 t1(2,2),t2(2,2),t3(2,2),t4(2,2),t5(2,2),t6(2,2),t7(2,2)
complex*16 tt(2,2),ss(2,2),ts(2,2),st(2,2)
integer*4 nl
c
c initialize and find the line parameters
c
pi=3.14159265358979
lamg=(3.0e10)/(dsqrt(er)*f)
vp=(3.0e10)/dsqrt(er)
iqc=(1.5911/dsqrt(sigma*(f/1.0e9)))*gbtw
iq=iqc+tand
q=dble(1.0)/iq
c
if(nl.eq.1) then
alpha=dble(0.0)
else
alpha=pi/(q*lamg)
endif
beta=(2.0*pi)/lamg
gam=dcmplx(alpha,beta)
yo=dble(1.0)/zo
c
c find the equivalent gap admittances
c
call gap_circuit(s,b,zo,lamg,ba,bb)
ya=dcmplx(dp0,ba)
yb=dcmplx(dp0,bb)
y1=ya
y2=y1
y3=yb
c

```

```

c   find the s-parameters
c
c      call s_pi(yo,y1,y2,y3,s5)
c      call s_line(z0,z0,gam,l1+(s/2.0),s6)
c      call s_disc(z0,zt,s7)
c
c   convert the s-parameters to t-parameters
c
c      call con_t(s5,t5)
c      call con_t(s6,t6)
c      call con_t(s7,t7)
c
c   multiply the matrices
c
c      call m_m(t5,t6,tt)
c      call m_m(tt,t7,ts)
c
c   convert back to s-parameters
c
c      call con_s(ts,ss)
c      write(6,*)f,10.0*dlog10(cdabs(ss(2,1)))
c
c      return
c      end
c
c   end of subroutine com_s
c
c*****
c
c   subroutine m_m
c
c      subroutine m_m(a,b,c)
c      complex*16 a(2,2),b(2,2),c(2,2)
c
c      multiply two 2 X 2 matrices
c
c      c(1,1)=a(1,1)*b(1,1)+a(1,2)*b(2,1)
c      c(1,2)=a(1,1)*b(1,2)+a(1,2)*b(2,2)
c      c(2,1)=a(2,1)*b(1,1)+a(2,2)*b(2,1)
c      c(2,2)=a(2,1)*b(1,2)+a(2,2)*b(2,2)
c
c      return
c      end
c
c   end of subroutine m_m
c

```

```

***** *****
c
c subroutine con_t
c
subroutine con_t(s,t)
complex*16 s(2,2),t(2,2)
c
c convert s-parameters to t-parameters
c
c t(1,1) = (dble(-1.0)*s(1,1)*s(2,2)+s(1,2)*s(2,1))/s(2,1)
c t(1,2)=s(1,1)/s(2,1)
c t(2,1)=s(2,2)/s(2,1)
c t(2,1) = (dble(-1.0)*s(2,2))/s(2,1)
c t(2,1)=dble(-1.0)*t(2,1)
c t(1,1)=(t(1,2)*t(2,1))*s(2,1)+s(1,2)
c t(2,2)=dble(1.0)/s(2,1)
c
c write(6,*)' t-par ',t(1,1)*t(2,2)-t(1,2)*t(2,1)
c
c return
c end
c
c end of subroutine con_t
c
***** *****
c
c subroutine con_s
c
subroutine con_s(t,s)
complex*16 t(2,2),s(2,2)
c
c convert t-parameters to s-parameters
c
c s(1,1)=t(1,2)/t(2,2)
c s(1,2)=(t(1,1)*t(2,2)-t(1,2)*t(2,1))/t(2,2)
c s(2,1)=dble(1.0)/t(2,2)
c s(2,2)=t(2,1)/t(2,2)
c s(2,2)=dble(-1.0)*s(2,2)
c
c return
c end
c
c end of subroutine con_s
c
***** *****
c
```

```

c subroutine s_disc
c
c subroutine s_disc(z1,z2,s)
c complex*16 z1,z2,ds,s(2,2)
c
c compute the s-parameters for a change in characteristic impedance
c
ds=z1+z2
c
s(1,1)=z2-z1
s(1,2)=dble(2.0)*cdsqrt(z1*z2)
s(2,1)=s(1,2)
s(2,2)=z1-z2
c
s(1,1)=s(1,1)*(1.0/ds)
s(1,2)=s(1,2)*(1.0/ds)
s(2,1)=s(2,1)*(1.0/ds)
s(2,2)=s(2,2)*(1.0/ds)
c
return
end
c
c end of subroutine s_disc
c
*****
c subroutine s_line
c
subroutine s_line(zo,z,gam,l,s)
complex*16 zo,z,ds,gam,ngam,s(2,2),sh,ch
real*8 l
c
c compute the s-parameters of a lossy line segment
c
ngam=dble(-1.0)*gam
sh=(cdexp(gam*l)-cdexp(ngam*l))
sh=sh/dble(2.0)
ch=(cdexp(gam*l)+cdexp(ngam*l))
ch=ch/dble(2.0)
ds=(dble(2.0)*z*zo*ch)+(((z*z)+(zo*zo))*sh)
c
s(1,1)=((z*z)-(zo*zo))*sh
s(1,2)=2*z*zo
s(2,1)=s(1,2)
s(2,2)=s(1,1)
c

```

```

s(1,1)=s(1,1)*(1.0/ds)
s(1,2)=s(1,2)*(1.0/ds)
s(2,1)=s(2,1)*(1.0/ds)
s(2,2)=s(2,2)*(1.0/ds)

c
return
end

c
c end of subroutine s_line
c

*****+
c
c subroutine s_pi
c
c
subroutine s_pi(yo,y1,y2,y3,s)
complex*16 yo,y1,y2,y3,s(2,2),p,d,q,ds
c
c compute the s-parameters of a pi circuit
c
d=(y1*y2)+(y2*y3)+(y3*y1)
q=y1+y2+(dble(2.0)*y3)
p=y1-y2
ds=(yo*yo)+(q*yo)+d
c
s(1,1)=(yo*yo)-(p*yo)-d
s(1,2)=dble(2.0)*yo*y3
s(2,1)=s(1,2)
s(2,2)=(yo*yo)+(p*yo)-d
c
s(1,1)=s(1,1)*(1.0/ds)
s(1,2)=s(1,2)*(1.0/ds)
s(2,1)=s(2,1)*(1.0/ds)
s(2,2)=s(2,2)*(1.0/ds)

c
return
end

c
c end of subroutine s_pi
c

*****+
c
c subroutine gap_circuit
c
subroutine gap_circuit(s,b,zo,lamg,ba,bb)
complex*16 zo
real*8 s,b,zot,yo,ba,bb,xa,xb,a1,a2,a3,a4,pi, lamg

```

```

c
c  compute the admittances of a stripline gap
c
pi=3.14159265358979
yo=dble(1.0)/dreal(z0)
c
ba=(-2.0*b)/lamg*dlog(dcos((pi*s)/(2.0*b)))
bb=(1.0*b)/lamg*dlog(1.0/(dtanh((pi*s)/(2.0*b))))
c
ba=ba*yo
bb=bb*yo
c
xa=1.0/ba
xb=1.0/bb
c
return
end
c
c  end of subroutine gap_circuit
c
*****subroutine compute_zo
c
c  subroutine compute_zo(b,t,w,er,zot)
real*8 b,t,w,zot,er,web,cf,tb,wb,wbt,aa,bb,pi,xx
pi=3.14159265358979
c
c  compute the characteristic impedance of a stripline
c
tb=t/b
wb=w/b
wbt=w/(b-t)
c
if(wb.ge.0.35) then
web=wb
else
web=wb-((0.35-wb)**2.0)/(1.0+(12.0*tb))
endif
c
aa=2.0*dlog((2.0-tb)/(1.0-tb))
bb=tb*dlog((1.0/((1.0-tb)**2.0))-1.0)
cf=aa-bb
c
aa=30.0*pi*(1.0-tb)
bb=web+(cf/pi)

```

```

zot=(1.0/dsqrt(er))*(aa/bb)
c
return
end
c
c end of subroutine compute_zo
c
***** ****
c
c subroutine c_gbtw
c
subroutine c_gbtw(b,t,w,z0,er,gbtw,g1btw)
real*8 b,t,w,pi,aa,bb,n1,n2,n3,n4,d1,d2,d3,d4,gbtw,z0,er,zz
real*8 dzb,dzt,dzw,z2,z1,zst,zt,tt,wt,g1btw,do
pi=3.14159265358979
zst=dble(1.0e-5)

c
c compute g(b,t,w)
c
c
c n1=dble(1.0)
c n2=(2.0*w)/(b-t)
c n3=(1.0/pi)*((b+t)/(b-t))*dlog(((2.0*b)-t)/t)
c aa=n1+n2+n3
c
c n1=(0.35-(w/b))/((b-t)*((1.0+12.0*(t/b))**2.0))
c n2=(t/b)*((17.45*b)+(35.0*w))
c n3=(-9.0*w)+(5.85*w*w/b)+(-32.4*(t*t/b))
c if(w/(b-t).lt.0.35) then
c bb=n1*(n2+n3)
c else
c bb=0.0
c endif
c
c d1=w+((2.0*b)/pi)*dlog(((2.0*b)-t)/((1.0*b)-t))
c d2=(-1.0*t/pi)*dlog((t*((2.0*b)-t))/((b-t)*(b-t)))
c
c zz=(z0*dsqrt(er))/(30.0*pi)
c gbtw=zz*((aa+bb)/(b-t))
c
call compute_zo(b,t,w,er,z1)
c
c take numerical partial derivatives
c
bt=b+zst
call compute_zo(bt,t,w,er,z2)

```

```

dzb=(z2-z1)/zst
c
tt=t+zst
call compute_zo(b,tt,w,er,z2)
dzt=(z2-z1)/zst
c
wt=w+zst
call compute_zo(b,t,wt,er,z2)
dzw=(z2-z1)/zst
c
gbtw=(dble(1.0)/z1)*(dzb-dzw-dzt)
g1btw=gbtw
c
c
if(w/b.lt.0.35) then
n1=w
n2=t/pi
n3=(t/pi)*dlog((dble(4.0)*pi*w)/t)
n4=dble(0.510)*(t*t*t)/(w*w)
do=dble(0.5)*(n1+n2+n3+n4)
n1=(dble(0.1592)*t)/w
n2=(dble(0.244)*t*t)/(w*w)
n3=(dble(0.162)*t*t*t)/(w*w*w)
n4=dble(0.1592)*dlog((dble(4.0)*pi*w)/t)
d1=dble(0.5)+n1+n2+n3+n4
d2=(d1*b)/do
d3=dble(1.0)+d2
d4=b*dlog((dble(4.0)*b)/(pi*do))
g1btw=d3/d4
endif
c
c
return
end
c
c end of subroutine c_gbtw
c
*****

```

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the scanned document**