Optimization Study of the Stripline Resonator Technique for Dielectric Characterization

by

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ABSTRACT

To properly design the microwave components such as transmission lines, filters, capacitors, inductors, and many others, it is important to know the characteristics of the construction materials at microwave frequencies. One of the most reliable techniques in material characterization at microwave frequencies is the coplaner coupled stripline resonator technique. This technique is an enhancement to the classical stripline resonator technique. In this technique, the measured resonance frequency and quality factor of the resonator are used to determine the complex permitivity.

One of the main problems in this technique is the proper modeling of the coupling gaps. In this dissertation we will introduce an accurate model of the coupling gap, which will shows that the capacitive behavior of the gap is not pure capacitive as known before, but it turns into more complex one at higher frequencies depending on the dimensions of the gap primarily.

The second main problem is the limitation in the frequency range for accurate measurements. At higher frequencies, the coupling reaches its peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value. In this frequency range, measurement of the dielectric properties looses its accuracy because the lowered Q values which means inaccuracies in determining the resonant frequencies as well as great error in determining the Q_c and Q_d terms.

In this dissertation, attempts to remedy this problem by introducing two different approaches to get an improved design for the coplaner coupled stripline resonator are presented.

The first approach to optimize the design of the coplaner coupled stripline resonator is based on optimizing the dimensions of the coplaner coupled stripline resonator three sections (coplaner, transition region, and the center stripline).

In the second approach, a reactive stub (via) is introduced in the coupling gap between the coplaner line and the center stripline. The added stub is designed to improve the Q values of the structure resonances. Simulations of different designs of the coplaner coupled stripline resonator using different stub dimensions are presented. Advantages and disadvantages of these designs as well as the solution to their resonance frequency shift problems are discussed as well.

TO MY FAMILY…

THE MEMORY OF MY FATHER,

MY MOTHER,

MY WIFE, MY DAUGHTERS

(KHOLOD, DONYA, DOHA),

MY BROTHERS, AND MY SISTER

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The past few years have seen tremendous progress in solid state devices used for microwave applications. 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. Also, the properties of the materials used in fabricating the circuit are very important as any anomalies result in degradation of electrical performance.

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 complex permittivity. Knowledge of the complex permitivity of microwave dielectric materials is of prime importance to designers of microwave circuits built using such materials. Any errors in the complex permitivity could lead to significant changes in the overall performance of the designed circuit.

Recently significant advances have been made in material characterization techniques. Many techniques are available for the measurement of the real part of the complex permitivity (dielectric constant), however, each technique is useful for certain kinds of materials and certain frequency ranges. Two of the most commonly used techniques for measuring material properties at microwave frequencies are cavity techniques and transmission lines techniques. Cavity methods involve modeling a cavity in some geometry with boundaries of finite conductivity filled with the material under test. This model is used to relate the measure transmission and reflection signals of a cavity to the characteristics of the material from which it was constructed. Transmission line techniques use an assumed model for the response of a dielectric material filled in 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.

Much fewer techniques are available for the accurate measurements of the loss tangent of low-loss materials and almost all of them utilize resonant cavities or other resonators. Some of the most commonly used techniques and which we will go through them in this thesis are the stripline techniques, stripline resonator techniques, and coplaner coupled stripline resonator techniques. The stripline consists of a narrow, flat strip of copper sandwiched between two outer layers of dielectric materials. The outer surfaces of the dielectric sheets are faced with copper foil. This stripline structure is very useful for broad band circuits, since it 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_o and a complex propagation constant $\gamma = \alpha + j\,\beta$. Using this model the material properties can be formed by time or frequency domain measurements.

Accurately measuring the complex propagation constant 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. The coplaner coupled stripline resonator configuration is fundamentally the same as that of the stripline resonator. The main difference is the replacement of the two stripline coupling sections by coplaner line sections which fabricated on the top surface of the structure. Coupling is determined by the overlap (or spacing) between the edges of the coplaner lines and the stripline sides. The coplaner coupled stripline resonator offers some advantages over the stripline resonator. The first advantage is the convenient connection to the launchers. The second advantage of the coplaner coupled stripline resonator is evident in the cases where the optimum stripline resonator gaps are too small and hence practically impossible to fabricate. In this case, increasing the overlap between the coplaner sections and the resonator section would yield a practical solution and give the same desired effect as that of a small gap. A third advantage is the ability to adjust the coupling between the coplanar line section and the resonator section by trimming the exposed overlap of the coplaner section.

In both configurations the S_{21} displays resonance when stripline length is a multiple of $\lambda/2$. Also, 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 factor 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 resonate frequencies of the resonators, it is possible to estimate the relative permitivity of the dielectric.

In such technique, the measured resonance frequency and quality factor of the resonator are used to determine the complex permitivity. In these techniques, neglecting radiation losses as well as errors in modeling the coupling gaps and end effects introduce errors in the measured permitivity. Furthermore, in the stripline resonator, several fabrication iterations may be necessary in order to obtain the proper gap size to provide acceptable coupling of the resonator to compromise between very strong coupling where radiation loss becomes significant and very weak coupling, which leads to difficulty in detecting resonance.

In this dissertation we will focus on the coplaner coupled stripline resonator technique. We will discuss its advantages and disadvantages over the stripline resonator technique. We will discuss the practical problems we met while using this technique in the material characterization measurements as well as the solutions to these problems.

The first issue we will discuss in this matter, is the proper design of the coupling gap in the coplaner coupled stripline resonator. The gap dimensions are expected to affect both the shape of the stripline resonances (and hence the quality factor Q) as well as the frequencies (f_0) at which they occur. In other words, the gap dimensions affect both f_0 and Q, which are the two primary values in determining the complex permitivity of the dielectric material. This makes it critical to properly design the gap transition region and choose its optimum dimensions. In order to have a complete appreciation of the effect of the gap dimensions on the response of the stripline resonator; we will simulate a set of stripline resonators with different gap dimensions. From the results of these simulations, we will be able to put the suitable modifications to the design of the coplaner coupled stripline resonator by controlling the gap dimensions.

One of the interesting results of these simulations is that the capacitive behavior of the gap is not pure capacitive as known before, but it turns into more complex one at higher frequencies depending on the dimensions of the gap. We will verify this result by driving the lumped element model of the gap using Pspice simulation software and comparing the S_{21} of the transition region using this lumped element model of the gap with S_{21} of the original design of the transition region using the IE3D simulation software.

The second issue we will discuss in this dissertation is the main problem of the coplaner coupled stripline resonator technique, which we met while using this technique in the practical material characterization measurements. This problem represents the limitation in the frequency range that, we can get good Q values (sharp resonances) during the measurements. This means we don't have enough sharp clean resonances to use in the calculations of the dielectric constant of the used material in this frequency range. At this frequency range, the coupling reaches its peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value. In this frequency range, measurement of the dielectric properties looses its accuracy because the lowered Q values means inaccuracies in determining the resonant frequencies as well as great error in determining the Q_c and Q_d terms. Therefore, we cannot accurately calculate the dielectric constant of the given material at this range of frequencies.

As the frequency requirements of the microwave integrated circuits goes higher and higher, the properties of the used material at these frequencies needs to be accurately characterized. To be able to accurately characterize the same dielectric material using the coplaner coupled stripline resonator technique at higher frequency range, we need to optimize the design of the coplaner coupled stripline resonator to extend the frequency range of the accurate measurements. In other words to increase the number of the sharp resonance we can get in this frequency range, which means accurate calculations of the dielectric constant of the used material at these frequencies. In this regard we will use in this dissertation two different approaches to get an improvement design for the coplaner coupled stripline resonator, which will extend the frequency range of the accurate measurements.

The first approach to optimize the design of the coplaner coupled stripline resonator is based on optimizing the dimensions of the coplaner coupled stripline resonator three sections (coplaner, transition region, and the center stripline). Intuitive designs will be simulated using the IE3D software and the results will be studied and analyzed. In stead of performing one comprehensive simulation of the whole resonator, regional simulation of the coplanar section, the transition (gap) section, and the stripline section will be performed separately. A composite characteristics of the coplaner coupled stripline resonator is then obtained by combining individual regional characteristics.

The idea of the second approach comes from the Pspice simulation of the gap in , which revealed that an additional shunt LC can designed to improve the gap performance in the coplaner coupled stripline resonator structure. This can be realized by introducing a vertical stub to either of the two gap conductors. The stub would bridge part of the vertical gap without shorting to the other conductor. The conductor vertical stub will be referred to as via in this work since it would be fabricated using the typical via fabrication methods. The inductance introduced by the via would depend on its cross sectional dimensions as well as its height. The capacitance component results from the surface area of via section and its relative position with respect to the ground conductors. In order to increase the design flexibility to allow a separate control for the C component, an additional plate is added to the bottom of the stub. Simulations of different designs of the coplaner coupled stripline resonator using different via and copper plate dimensions will be made. Comparisons between the S_{21} of the new designs and the original one as well as the recommended optimum designs will be presented. A complete study and analysis of the new designs will be handled. Advantages and disadvantages of these designs as well as the solution to their resonance frequency shift problems will be discussed in this dissertation.

In this dissertation, Chapter 2 will present a brief overview for three of the used techniques in material characterization. These three techniques are the stripline technique, the conventional stripline resonator technique, and finally the coplaner coupled stripline resonator technique. In Chapter 3, the equations and theory necessary to relate the response of coplaner coupled stripline resonator to the characteristics of the materials from which it is constructed will be introduced. In Chapter 4, the effect of the coupling gap dimensions on both the f_0 and Q, which are the two primary values in determining the complex permitivity of the dielectric material will be discussed. The lumped element model of the coupling gap as well as a recommended LC shunt resonance branch to the design of this coupling gap will be presented. In Chapter 5, the two used approaches; (by optimizing the dimensions of the coplaner coupled stripline resonator three sections, and by using a via with different dimensions and shapes between the coplaner line and the stripline); in optimizing the design of the coplaner coupled stripline resonator will be presented. The results of the simulations of these new designs as well as the comparisons between these new designs and the original design will be presented and analyzed. In Chapter 6, the study and the analysis in the effect of using the via on the resonance frequency of the coplaner coupled stripline resonator as well as its possible solution will be discussed. Chapter 7 includes a summary and conclusions.

Chapter 2

Material Characterization Using the Coplaner Coupled Stripline Resonator Technique

2.1 Introduction

Using stripline resonators for material characterization is often the most appropriate technique to use at microwave frequencies. This is the case for substrate materials used to construct microwave planar circuits. Other planar resonator configurations include the microstrip resonator, the ring resonator, and the Tee resonator [1,2,3,4]. They all share the same basic concepts as these of the stripline resonator [5,6].

The stripline resonator configuration is favored over the others because of its simple configuration as well as it involves the fewest approximation in its analysis.

This chapter will start with a brief overview of the stripline configuration. Next the conventional stripline resonator technique for material characterization is reviewed. Finally the coplanar coupled stripline resonator is introduced and discussed in detail.

2.2 The Stripline Configuration (SL)

A cross section of the stripline configuration is shown in Figure (2.1). It depicts a narrow, flat strip of copper sandwiched between two outer layers of the dielectric materials. The outer surfaces of the dielectric sheets are faced with copper foil.

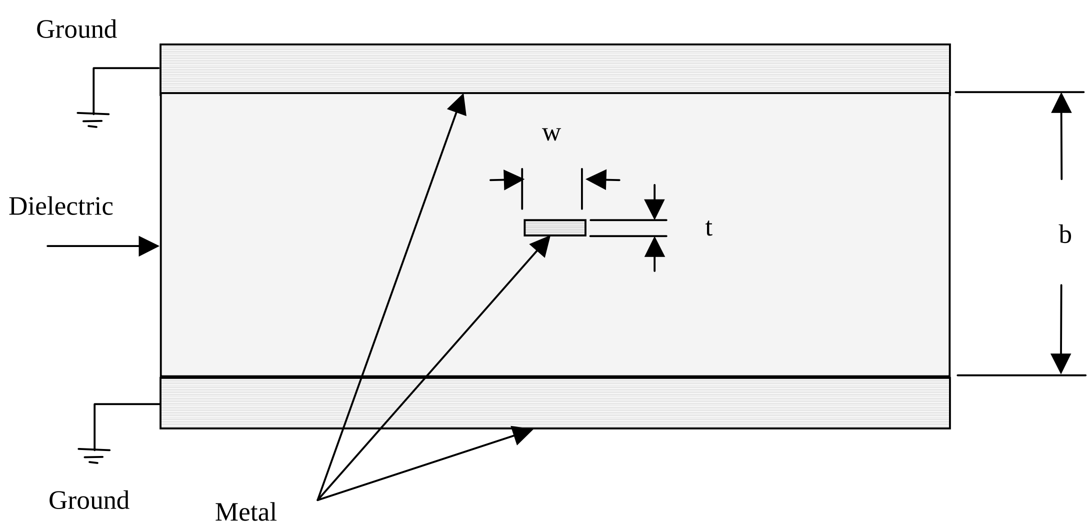


Fig 2.1 Stripline cross section

In the most common form of stripline, the circuit is photo-etched on one side of a double copper-clad laminate, then laid against the dielectric side of a single-clad board. The sandwich produced is held together by means of either eyelets through the board, screws, heavy clamping plates, or a resin bond formed under heat and pressure. Connections to the stripline are made either at the edge of the package or through the side; either special stripline end launch connectors or metal tabs are used.

It is helpful to recognize that the stripline structure may be interpreted as a flattened form of coaxial cable [7,8,9]. This relationship is demonstrated in Figure (2.2).

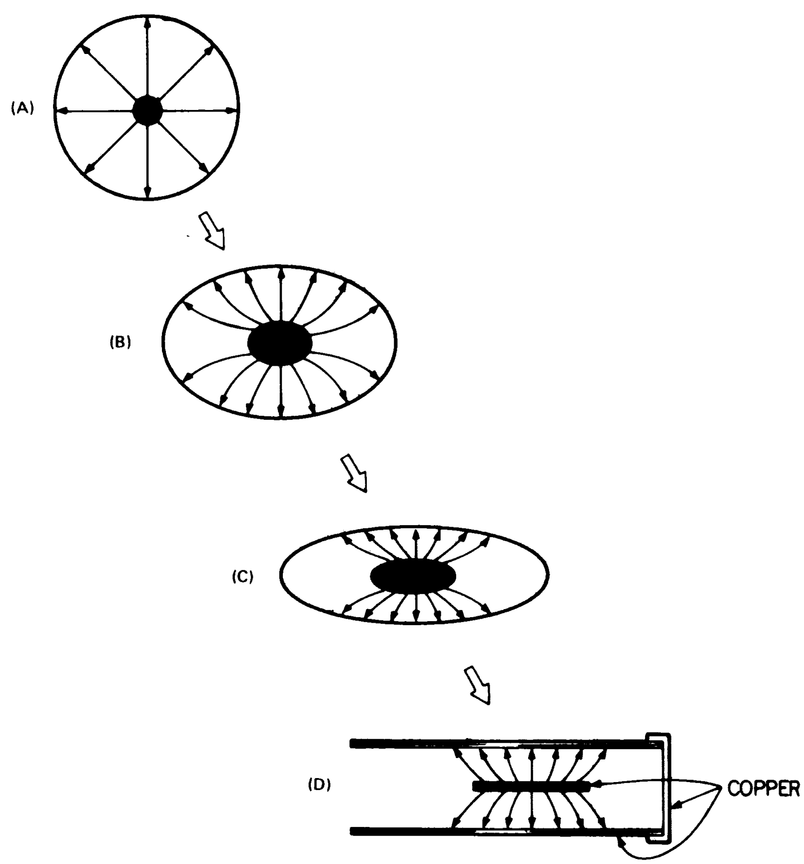


Fig 2.2 Evolution of stripline from coaxial cable

The arrows indicate the electric field between inner and outer conductors at an instant when the inner conductor is positive. When the lines are far apart, the field is weak. There is no field outside a coaxial cable because the outer conductor is continuous.

Proceeding from step (c) to step (d) in Figure (2.2), the outer conductor is interrupted and it becomes two plates – but the field extends only a short distance on each side of the center strip. If the plates extend well beyond the strip, the field at their edge is essentially zero. Therefore, properly designed stripline, like coaxial cable, is largely self-shielding, though some leakage may occur through the exposed edges of the dielectric. To counteract this potential problem, a conductive tape or strap is folded over the edge of the package to make contact with and to electrically bond together the two ground planes, as shown in Figure (2.2d).

When the dielectric is solid (as opposed to being air), as is usually the case, the speed at which the wave travels along the transmission line (velocity of propagation) is reduced, as is the wavelength [10,11]. The actual stripline wavelength (λ) is equal to the free space wavelength (λ_0) divided by the square root of the relative permittivity (ε_r):

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

To emphasize the importance of the dielectric constant to the physical size of stripline, the table below shows five frequencies and their wavelengths in air and in two types of dielectrics [7].

Table 2.1 Wavelength versus frequency at different materials

Frequency (GHz)	λ_0 (air) in inch	λ (ϵ_r =2.55) in inch	λ (ϵ_r =9.00) in inch
.50	23.60	14.80	7.87
1.00	11.80	7.42	3.93
3.00	3.93	2.47	1.31
5.00	2.36	1.48	.79
12.00	.98	.62	.33

We can see from this table that, as the dielectric constant of the measured material increases, the required size of the stripline components may be reduced [12,13,14]. Because the dielectric constant controls the wavelengths in the stripline circuit, it is a critical property in all applications; however, the thickness of the dielectric is often of equal importance. The characteristic impedance (Z_0) – a fundamental design parameter for all stripline circuits – depends on the dielectric constant [15,16,17], the width and thickness of the conductor, and the thickness of the dielectric layers.

This structure of the stripline with two ground planes as shown in figure 2.1 has a much higher quality factor than the microstrip line. Therefore it is more suitable for on-line measurement of sheet like materials and material layers, when the material can't be touched or the layer is thick. Also, this stripline structure is very useful for broadband circuits, since it can be modeled by assuming TEM propagation and using a standard lossy transmission line model [18]; 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 [19,20]. This stripline technique depends 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.

2.3 The Stripline Resonator Technique for Material Characterization (SLR)

Resonant structures are extensively used network elements in the realization of various microwave components [21]. At low frequencies, resonant structures are invariably composed of the lumped elements. As the frequency of operation increases, lumped elements in general can't be used. Microwave resonant circuits can be realized by various forms of transmission lines. Conventional resonators consist of a bounded electromagnetic field in a volume enclosed by metallic walls. The electric and magnetic energies are stored in the electric and magnetic fields, respectively, of the electromagnetic field inside the structure and the equivalent lumped inductance and capacitance of the structure can be determined from the respective stored energy [22,23,24].

Accurately measuring the complex propagation constant 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 a stripline as shown in Figures (2.3), (2.4).

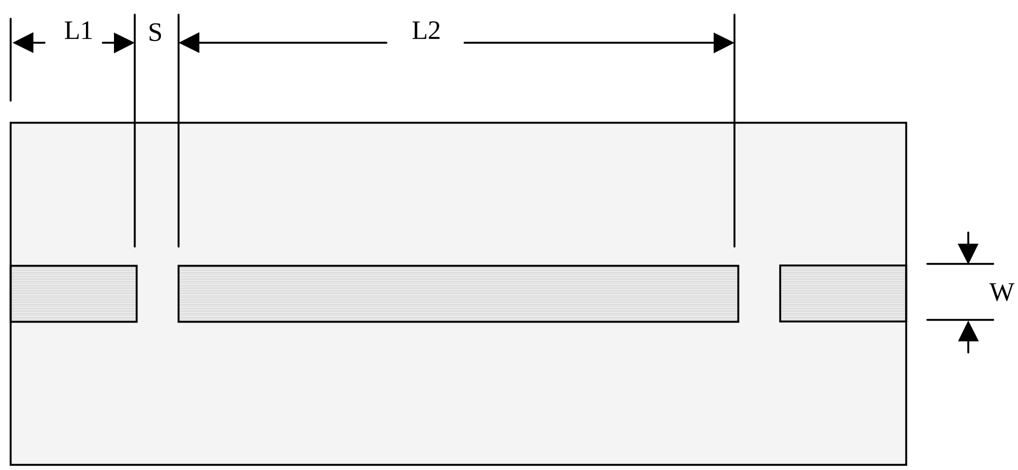


Fig 2.3 Stripline resonator configuration (top view)

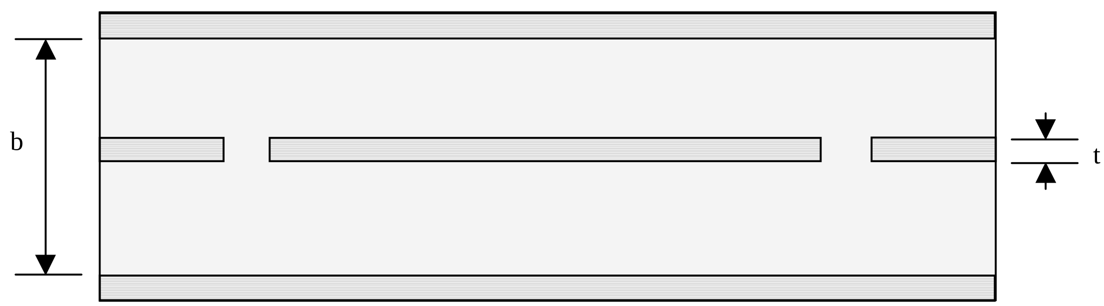


Fig 2.4 Stripline resonator configuration (side view)

Using this stripline resonator, the attenuation factor can be determined more accurately than the stripline technique. This can be achieved by assuming 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 permitivity of the dielectric [25]. This method is advantageous because it gives the material characteristics at a specific frequency and produces corresponding results even with materials whose characteristics vary with frequency.

2.4 Coplaner Coupled Stripline Resonator Technique (CCSLR):

The coplaner coupled stripline resonator configuration is fundamentally the same as that of the stripline resonator. The main difference is the replacement of the two striplines coupling sections by coplanar line sections as shown in Figures (2.5), (2.6).

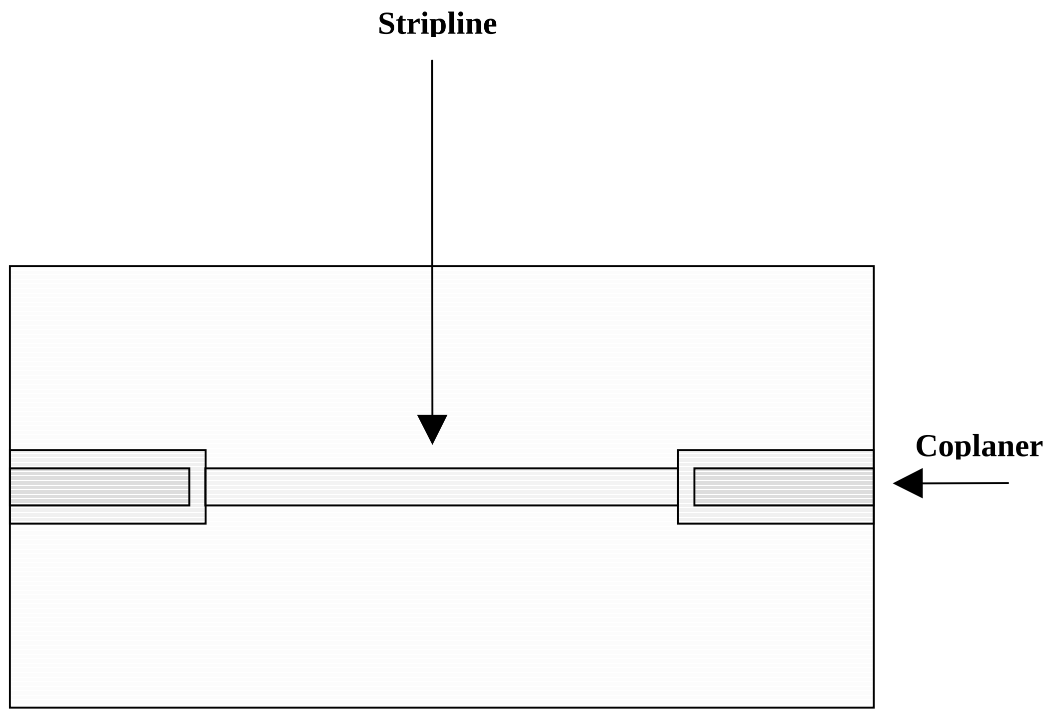


Fig 2.5 Coplaner coupled stripline resonator

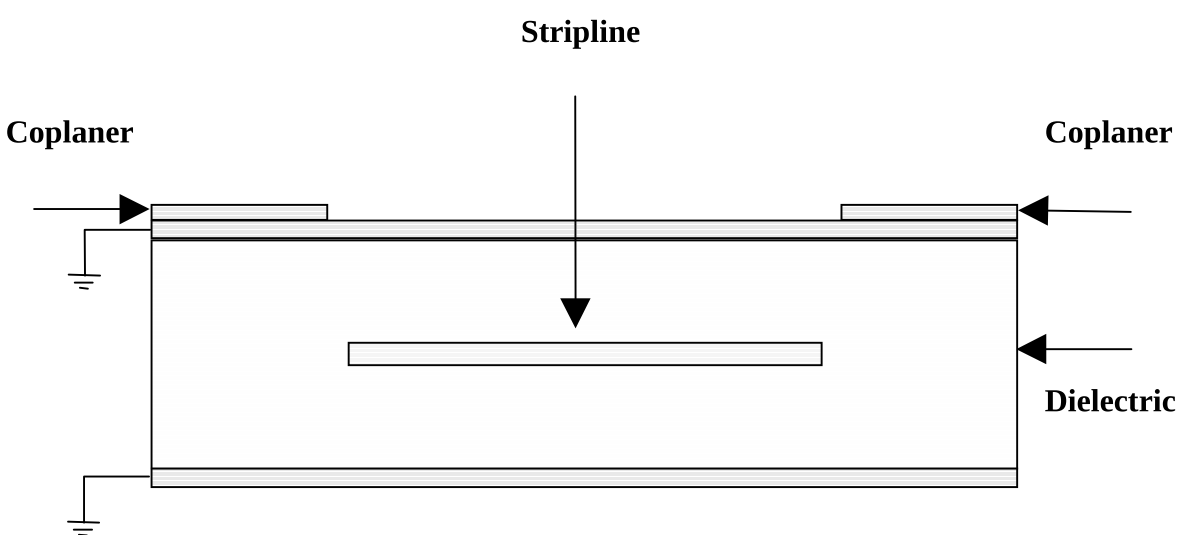


Fig 2.6 Coplaner coupled stripline resonator

As shown in the figures, the middle stripline resonator is now coupled via two coplanar line sections at either end. The coplanar line sections are fabricated on the top surface of the structure. Coupling is determined by the overlap (or spacing) between the edges of the coplanar lines and the stripline sides.

This new configuration was introduced by the researchers at Virginia Tech. [25] and offers a few advantages as discussed below. The first advantage of the CCSLR over the SLR is the convenient connection to the launchers. The coplanar ends of the structure are more convenient to connect to on both the center strip and the ground planes as exposed and can easily be connected to. The second advantage of the CCSLR is evident in the cases where the optimum SLR gaps are too small and hence practically impossible to fabricate. In these cases, increasing the overlap between the coplanar sections and the resonator section would yield a practical solution and give the same desired effect as that of a small gap. A third advantage is the ability to adjust the coupling between the coplanar line section and the resonator section. In a conventional SLR structure, once fabricated, it is impossible to adjust the gap dimension, which means no adjustment of the coupling is possible. However, in the fabricated CCSLR structure, the exposed overlap of the coplanar section may be trimmed to adjust its coupling to the buried stripline resonator section.

As in the case of stripline resonator the S_{21} displays resonances when stripline length is a multiple of $\lambda/2$. Also 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 permitivity of the dielectric. The details of the theoretical explanation of this technique will be discussed in the following section.

Chapter 3

Theory and Analysis of the Coplaner Coupled Stripline Resonator Technique

3.1 Introduction

This part presents the equations and theory necessary to relate the response of stripline resonator to the characteristics of the materials from which it is constructed. It begins with equations for the computation of the characteristic impedance of stripline which are used to derive the method of separation the loss terms based on the theoretical variation of conductor loss with stripline dimensions. This part also describes the method, which relates the resonant frequency of the resonator to the relative permitivity of the dielectric. The analysis presented in this section is equally and valid for both the SLR configuration and the CCSLR since it is related the resonator section (which is a stripline in both cases).

3.2 Characteristic Impedance

For an ideal stripline with a zero-thickness perfectly conducting center strip, the characteristic impedance is given exactly by [26]

$$Z_0 = \frac{30\pi K(k')}{\sqrt{\varepsilon_r}\,K(k)} \qquad (3\text{-}1)$$

where:

ε_r ... is the relative permittivity of the dielectric

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

$$K(x) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - x^2 \mathrm{Sin}^2\theta}} \qquad (3\text{-}2)$$

and

$$k' = \mathrm{sech}\,\frac{\pi w}{2b}, \qquad k = \tanh\frac{\pi w}{2b} \qquad (3\text{-}3)$$

where

w ... is the center strip width

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 a finite conductivity.

One of the most useful approximate formulas is given by (I.J. Bahl and Ramesh Gary, (1978) " A Designer's Guide to Stripline Circuits", Microwaves [27,28] as:

$$Z_0 = \frac{30\pi[1 - \frac{t}{b}]}{\sqrt{\varepsilon_r}\,[\frac{w_e}{b} + \frac{c_f}{\pi}]} \qquad (3\text{-}4)$$

where

$$c_f = 2\ln\left[\frac{1}{\left[1-\frac{t}{b}\right]}+1\right]-\frac{t}{b}\ln\left[\frac{1}{\left[1-\frac{t}{b}\right]^2}-1\right] \qquad (3\text{-}5)$$

For wide strips with $\frac{w}{(b-t)} \geq 0.35$, the effective center strip width, w_e, is defined by

$$\frac{w_e}{b} = \frac{w}{b} \qquad (3\text{-}6)$$

While, in the case of a narrow strip, where $0.05 \leq \frac{w}{(b-t)} \leq 0.35$, w_e is given by the empirical formula,

$$\frac{w_e}{b} = \frac{w}{b} - \frac{\left[0.35-\frac{w}{b}\right]^2}{1+12\frac{t}{b}} \qquad (3\text{-}7)$$

Both expressions (3-6), and (3-7) for w_e were found to be within 1 percent of measured data for $\frac{t}{b} \leq 0.25$.

The formulas given above are the same as the formulas in Cohn [26], except that Cohn does not use the empirical correction for the narrow strip case.

Instead, Cohn uses an equivalent round conductor approximation for the narrow strip region of $\frac{w}{b-t} \leq 0.35$

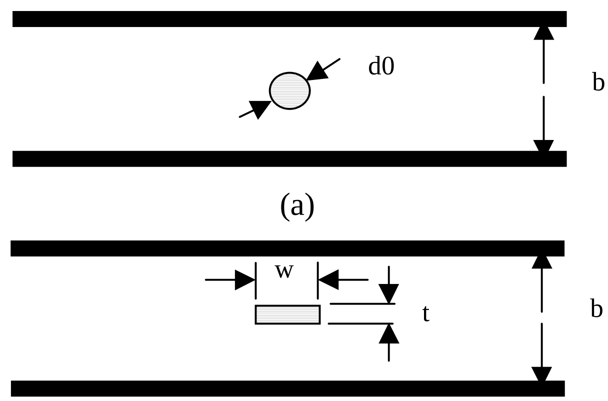


Fig 3.1 Center conductors of small cross section yielding equivalent characteristic impedance

The narrow strip characteristic impedance for Cohn is as follows:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4b}{\pi d_0}\right] \qquad (3\text{-}8)$$

where

d_0 ... 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_0 can be found from Figure (3.2), which is a plot of $\frac{d_0}{d'}$ versus $\frac{d''}{d'}$

where

d' ... is the larger dimension

d'' ... is the smaller of the dimensions w and t for $\frac{d''}{d'} \leq 0.11$, a very good approximate formula for computing d_0 is given by [26]

$$\frac{d_0}{d'} = \frac{1}{2}\left[1 + \frac{d''}{\pi d'}\left[1 + \ln\frac{4\pi d'}{d''} + 0.51\left[\frac{d''}{d'}\right]^2\right]\right] \tag{3-9}$$

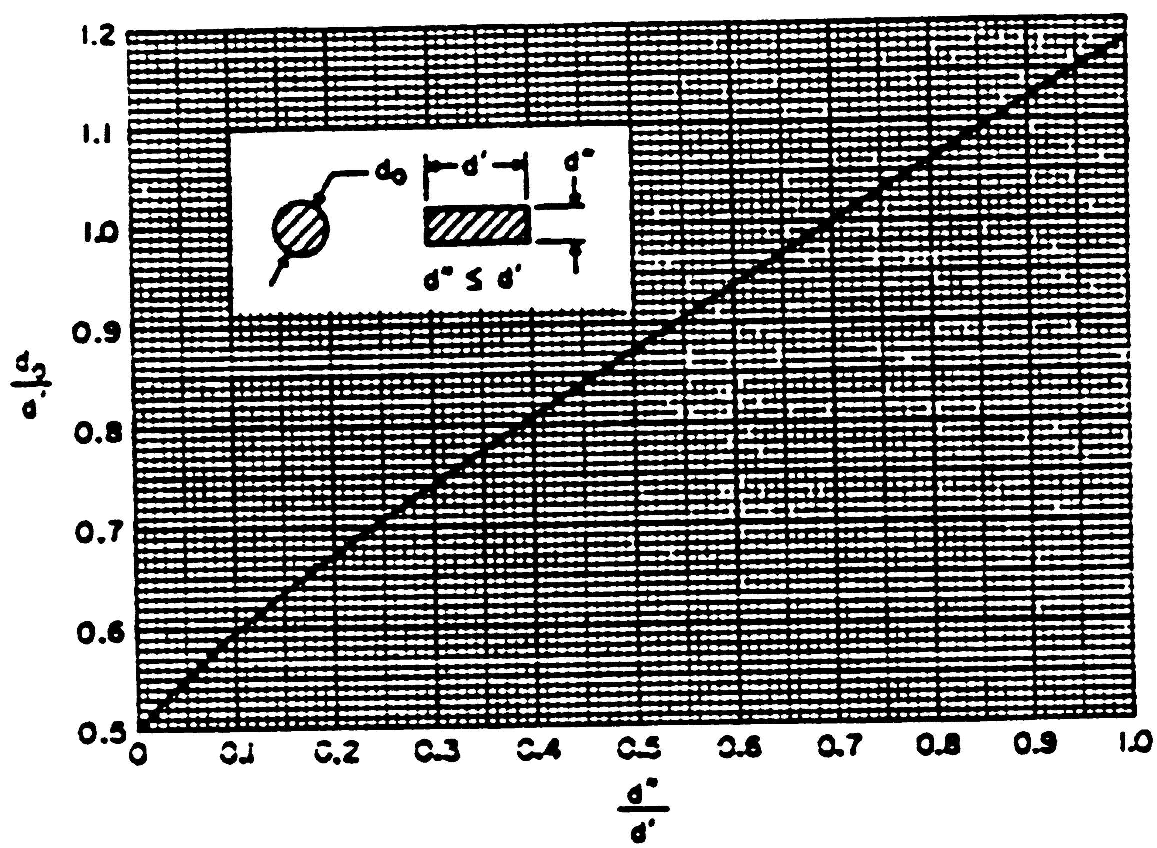


Fig 3.2 Equivalence between a rectangular and circular cross section

3.3 Resonance Frequencies of the Stripline Resonator

Using frequency domain measurement, (e.g. using a vector network analyzer), we can calculate the relative permitivity of the dielectric from the output resonance frequencies of the stripline resonator. Assuming λ_g is the wavelength in the stripline at the frequency fr, we can write the following relation in accordance to the theory of stripline,

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}} \tag{3.10}$$

where

λ_0 ... is the wavelength of the wave with frequency fr in free space,

$$\lambda_0 = \frac{c}{f_r} \tag{3.11}$$

When the length L of the stripline section is the integer multiples of $\frac{\lambda g}{2}$, the line becomes resonant. At this time, the output signal of the resonator achieves its maximum value. Hence, the resonant condition for a line resonator can be written as,

$$L = n \cdot \frac{\lambda_g}{2} \tag{3.12}$$

From equations (3.10), (3.11), and (3.12) we can write the relation between the measured resonance frequencies of the stripline resonator, f_r and the relative permitivity of the used dielectric in this resonator, ε_r as follows,

$$\varepsilon_r = \left(\frac{c}{2 \frac{f_r}{n} L} \right)^2 \tag{3.13}$$

where

c… is the speed of the light in free space.

f_r … is the resonant frequency.

ε_r … is the relative permittivity.

L … is the center strip length.

n =1,2,3, … is the order of the resonance.

One of the main difficulties with stripline resonator technique, is caused by the fringing field at the gap discontinuities. Therefore, a correction factor ΔL should be accounted for fringing and the center strip length L in equation (3.13) should be replaced by an effective center strip length L' [18]. L' is given as,

$$\mathbf{L}' = \mathbf{L} + \mathbf{2}\Delta\mathbf{L} \tag{3.14}$$

Through the S21 measurement, we can get the resonant frequency and using equation (3.13), and (3.14) we can calculate the relative permitivity of the used dielectric material. Also we can calculate the measurement errors from equation (3.15), which is derived from equation (4.13).

$$\frac{\Delta\varepsilon_{\mathbf{r}}}{\varepsilon_{\mathbf{r}}} = -\mathbf{2}\left[\frac{\Delta\mathbf{f}}{\mathbf{f}} = \frac{\Delta\mathbf{L}}{\mathbf{L}}\right] \tag{3.15}$$

3.4 Quality Factor in Stripline Resonator

The quality factor Q_0 of a low loss stripline resonator can be expressed as:

$$\frac{1}{Q_0} = \frac{1}{Q_c} + \frac{1}{Q_e} + \frac{1}{Q_r} + \frac{1}{Q_d} \qquad (3\text{-}16)$$

where

Q_c ... is the term due to loss in the conductor

Q_e ... is the term due to end radiation loss

Q_r ... is the term due to the side radiation loss

Q_d ... is the term due to the dielectric loss tangent

Measurements have shown that for most cases,

$\frac{1}{Q_e} + \frac{1}{Q_r}$ is less than one percent of the value of $\frac{1}{Q_0}$, [29].

Neglecting the radiation terms, (3-16) can be approximated by

$$\frac{1}{Q_0} = \frac{1}{Q_c} + \frac{1}{Q_d} \qquad (3\text{-}17)$$

For lines with small attenuation constant α, the quality factor of the line resonator can be related to α as:

$$Q = \frac{\pi\sqrt{\varepsilon_r}}{\alpha\lambda} \qquad (3\text{-}18)$$

provided that $\alpha \le \beta$ and $\alpha\ell \le 1$

where

β ...is the imaginary part of the complex propagation constant

ℓ ...is the length of the resonant transmission line.

The dielectric attenuation constant α_d is related to the dielectric loss tangent tan δ as given in [26] by

$$\alpha_d = \frac{\pi\sqrt{\varepsilon_r}}{\lambda_0} \tan \delta \tag{3-19}$$

where

λ_0 ... is the wavelength in free space.

Substituting by (3.19) in (3.18) gives

$$\frac{1}{Q_d} = \tan \delta \tag{3.20}$$

Using the same equation (3.18), we can determine the conductor loss term if α_c (attenuation due to conductor loss) is known. It is possible to find α_c by considering the incremental change in inductance per incremental change in stripline dimensions [26].
This method gives

$$\alpha_c = \frac{R_s\sqrt{\varepsilon_r}}{753.2\, Z_0} \frac{\delta Z_0}{\delta n} \quad \text{[Nepers/cm]} \tag{3.21}$$

where

R_s ... is the sheet resistivety of the stripline conductor (cladding)

$$R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} \tag{3-22}$$

where

f ... is the frequency

μ_0 ... is the permeability

σ ... is the conductivity of the conductor

In the case of TEM wave propagation and in a stripline

$$\frac{\delta Z_0}{\delta n} = 2\frac{\delta Z_0}{\delta b} - 2\frac{\delta Z_0}{\delta w} - 2\frac{\delta Z_0}{\delta t} \tag{3.23}$$

Substituting equation (3.22) & (3.23) in equation (3.21) gives

$$\alpha_c = \frac{\sqrt{\pi f \varepsilon_r \mu_0}}{376.6\, Z_0 \sqrt{\sigma}}\left[\frac{\delta Z_0}{\delta b} - \frac{\delta Z_0}{\delta w} - \frac{\delta Z_0}{\delta t}\right] \tag{3.24}$$

Which is then substituted in (3.18) to yield

$$\frac{1}{Q_c} = \frac{1.5911}{\sqrt{\sigma f}}\frac{1}{Z_0}\left[\frac{\delta Z_0}{\delta b} - \frac{\delta Z_0}{\delta w} - \frac{\delta Z_0}{\delta t}\right] \tag{3.25}$$

where

σ ... is the conductivity of the cladding in S/m

f ... is the frequency in GHZ

b, t, w ... are the strip line dimensions in cm

Equation (3-25) can be expressed in the more general form

$$\frac{1}{Q_c} = \frac{1.5911}{\sqrt{\sigma f}}\, g(b,t,w) \tag{3.26}$$

where

$$g(b,t,w) = \frac{1}{Z_0}\left[\frac{\delta Z_0}{\delta b} - \frac{\delta Z_0}{\delta w} - \frac{\delta Z_0}{\delta t}\right] \tag{3.27}$$

For the wide strip case, using equation (3.4) in equation (3.27) gives

$$g_1(b,t,w) = \left[\frac{1 + \frac{2w}{b - t} + \frac{1}{\pi}\frac{b+t}{b-t}\ln\frac{2b - t}{t}}{w + \frac{2b}{\pi}\ln\frac{2b - t}{b - t} - \frac{t}{\pi}\ln\frac{t(2b - t)}{(b - t)^2}} \right] \quad \mathbf{cm^{-1}} \tag{3.28}$$

This equation is valid for $\frac{w}{b-t} \geq 0.35$ and $\frac{t}{b} \leq 0.25$

For the narrow strip case:

$$g_2(b,t,w) = \frac{1}{b \ln \frac{4b}{\pi d_0}}\left[1 + \frac{b}{d_0}\left[\frac{1}{2} + k_1\frac{d''}{d'} - k_2\left[\frac{d''}{d'}\right]^2 + \frac{1}{2\pi}\ln\left[\frac{4\pi d'}{d''}\right]\right]\right] \mathbf{cm^{-1}} \tag{3.29}$$

This equation 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, k_1 = 0.1592, and k_2 =0.244.

By substituting equation (3.14) and (3.20) into equation (3.11) it is possible to write

$$\frac{1}{Q_0} = \frac{1.5911}{\sqrt{\sigma f}} g(b,t,w) + \tan\delta \tag{3.30}$$

Plotting $\frac{1}{Q_0}$ versus $g(b,t,w)$ results in a straight line with a slope $m = \frac{1.5911}{\sqrt{\sigma f}}$, and a y-intercept $b = \tan\delta$. This gives a method for separating the loss terms by producing multiple stripline resonators and plotting their unloaded quality factors versus $g(b,t,w)$.

3.5 Dielectric Characterization Using the Coplaner Coupled Stripline Resonator

In summary, we can say that, 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 dimension be varied sufficiently such that a good plot of $\frac{1}{Q_0}$ versus $g(b,t,w)$ can be obtained and consequently an accurate value of the dielectric loss tangent tan δ [25]. Since the thickness of the dielectric determines the b dimension and the thickness of the metal cladding determine the t dimension, it is not feasible to vary either of these two dimensions. This means that a series of resonator must be designed with varying center strip width, w. The length L, of the center strip must be chosen so that the resonant frequencies occur within the frequency range at which the material properties are to be characterized.

We can get a complete characterization for the used material in our stripline resonator by calculating the relative permitivity. This can be done by measuring S21 using the frequency domain measurements from which we can get the resonance frequencies of the stripline resonator and using equation (3.13) we can calculate the relative permitivity of the dielectric material at these frequencies [25]. Also, we can calculate the measurement errors using equation (3.15).

Chapter 4

Proper Design of Resonator Gap

4.1 Introduction

For the CCSLR configuration under consideration in this work, Figures (3.5), (3.6), the gap is defined as the transition / isolation region between the coplaner line and the stripline. The gap dimensions are expected to affect both the shape of the stripline resonances (and hence the quality factor Q) as well as the frequencies (f_0) at which they occur. In other words, the gap dimensions affect both f_0 and Q, which are the two primary values in determining the complex permitivity of the dielectric material. This makes it critical to properly design the gap transition region and choose its optimum dimensions.

4.2 EM Simulation for the Effect of Gap on Resonator Response

In order to have a complete appreciation of the effect of the gap dimensions on the response of the stripline resonator, we need to simulate a set of stripline resonators with different gap dimensions. From the results of these simulations, we will be able to put the suitable modifications to the design of the stripline resonator by controlling the gap dimensions.

One of the most efficient electromagnetic simulation software is the Zeland field simulation software IE3D. It is an integral equation, method of moment, full-wave electromagnetic simulator. It includes layout editor, electromagnetic simulator, schematic editor and circuit simulator, near field calculation program, format converter, as well as current and field display program. The IE3D employs a 3D non-uniform triangular and rectangular mixed meshing scheme. It solves the current distribution, network s-parameters, radiation patterns and near field on an arbitrarily shaped and oriented 3D metallic structure in a multi-layered dielectric environment.

Using the IE3D simulation software, we performed several simulations for the stripline resonator's transition region between the coplaner line and the center stripline at different overlap (coupling) dimensions. In this regard a portion of the coplanar line section (190 mil) and a portion of the stripline section (230 mil) were simulated with varying overlap region to study the coupling characteristics of the transition region.

Figure (4.1) shows the simulated transition region at different overlap dimensions between the coplanar line and the center stripline. In Figure (4.1a) there is no overlap between the coplanar line and the center stripline (0-mil overlap). In Figure (4.1b) the overlap between the coplanar line and the center stripline is 200-mil. Figure (4.1c) shows a 100- mil gap between the coplanar line and the center stripline (-100 mil overlap).

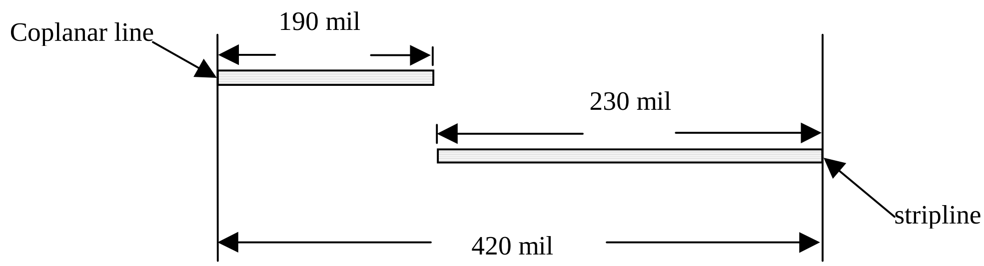


Fig 4.1a

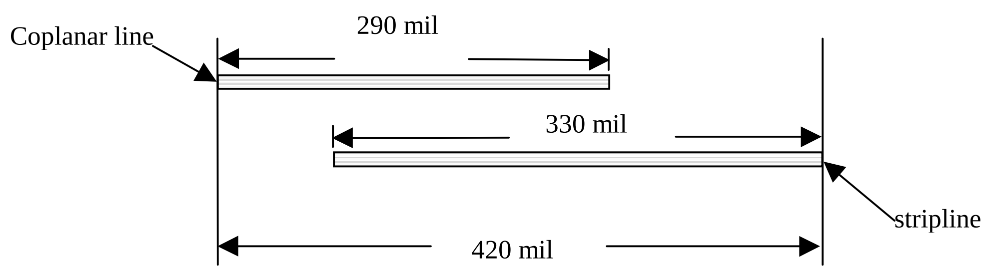


Fig 4.1b

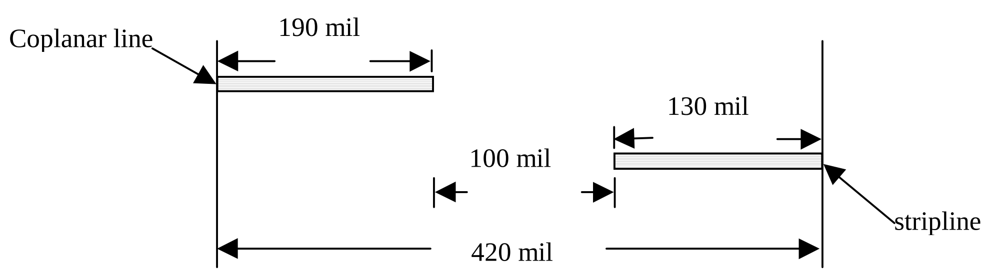


Fig 4.1c

Fig 4.1 Simulated transition region at different overlap between the coplaner line and the center stripline

The S_{21} vs. frequency results of these simulations were obtained. A sample of the results is shown in Figure (4.2). Examining the S_{21} vs. frequency results for different overlaps, the following observation can be made:

- A transition region with a large gap would cause the coupling to be very week to observe resonance.
- A transition region with a narrow gap would increase external loading effects that degrade the quality factor of resonance, also decrease the frequency range of operation of the resonator.
- The capacitive behavior of the gap turns into more complex one above some certain frequency depending on the dimensions of the gap, as we will see in the next section from the Pspice model of the gap.
- A relatively small overlap would help improve the behavior of the gap at higher frequencies.

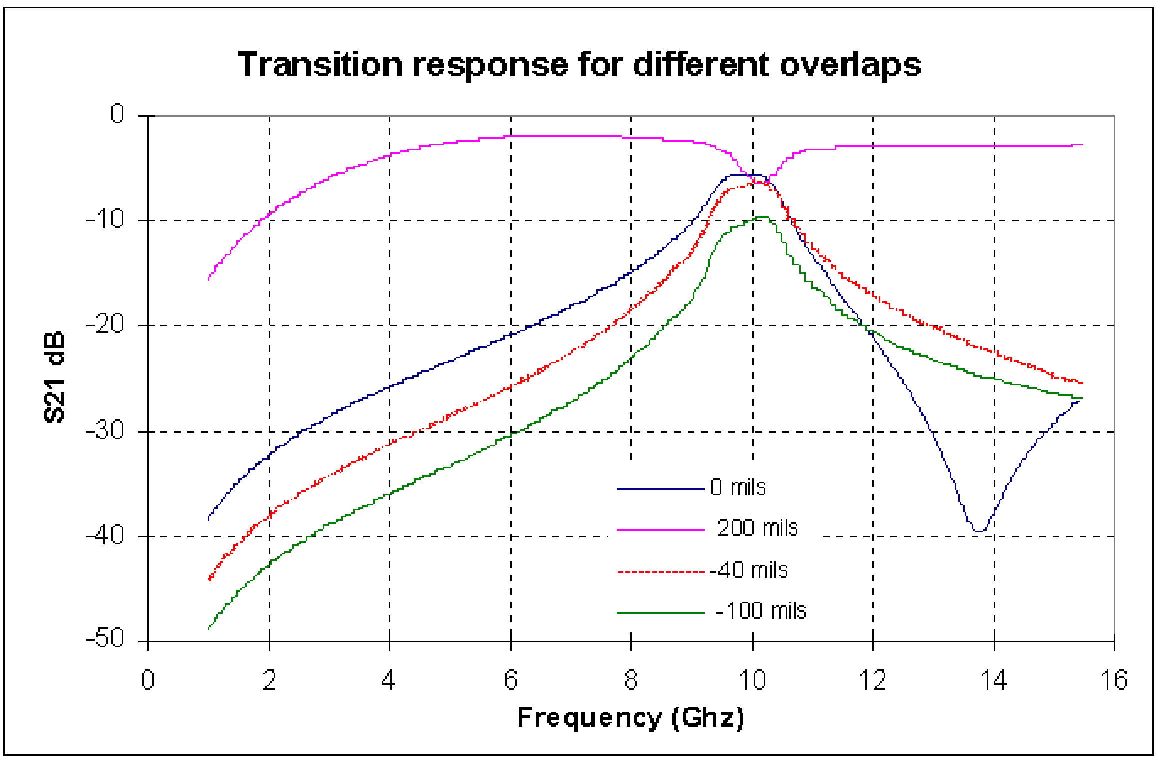


Fig 4.2 Transition response for different overlaps

4.3 Pspice Modeling of the Gap

As we had mentioned before, the capacitive behavior of the gap turns into more complex one above some certain frequency depending on the dimensions of the gap [30,31]. In this section we will try to verify that observation, using the Pspice software. Using the S21 values from IE3D simulation of transition region, we can drive a lumped element model of the gap using Pspice software.

We will model the transition region using the Pspice software including a part from the coplaner line, the overlap (coupling region), and a part from the center stripline. The result of the Pspice modeling is given in Figure (4.3). This model is derived by trial and error while comparing S_{21} of the Pspice model to that of the IE3D simulation. The S_{21} comparison corresponding to the model of Figure (4.3) is given in Figure (4.4). It is seen from the figure that a good agreement in S_{21} is achieved indicating good modeling accuracy.

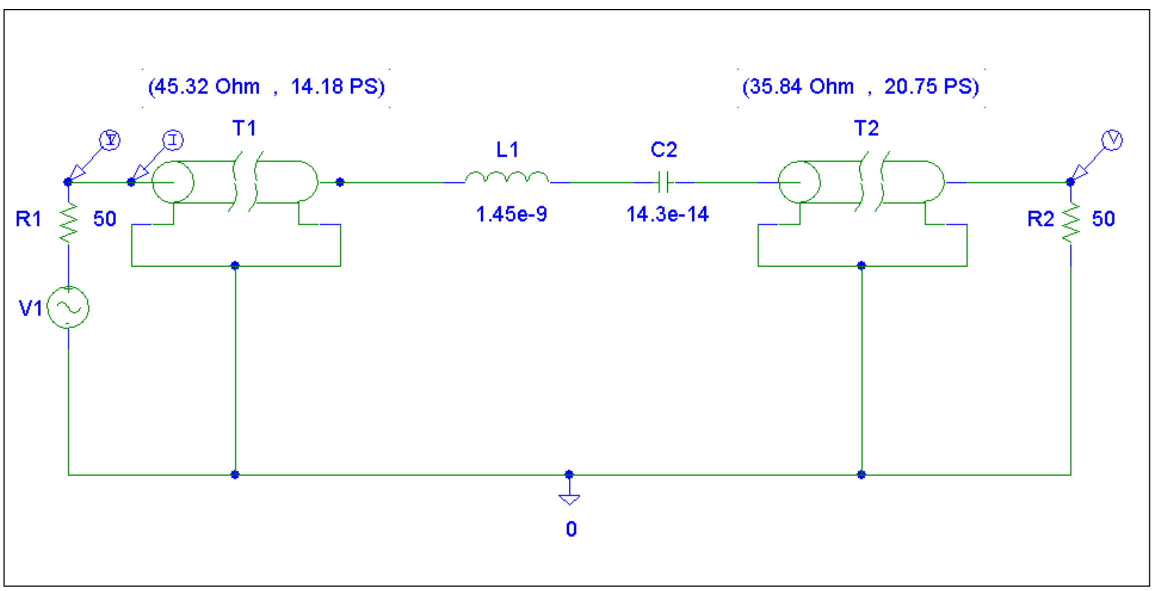


Fig 4.3 Pspice model for a transition of 0 mils overlap

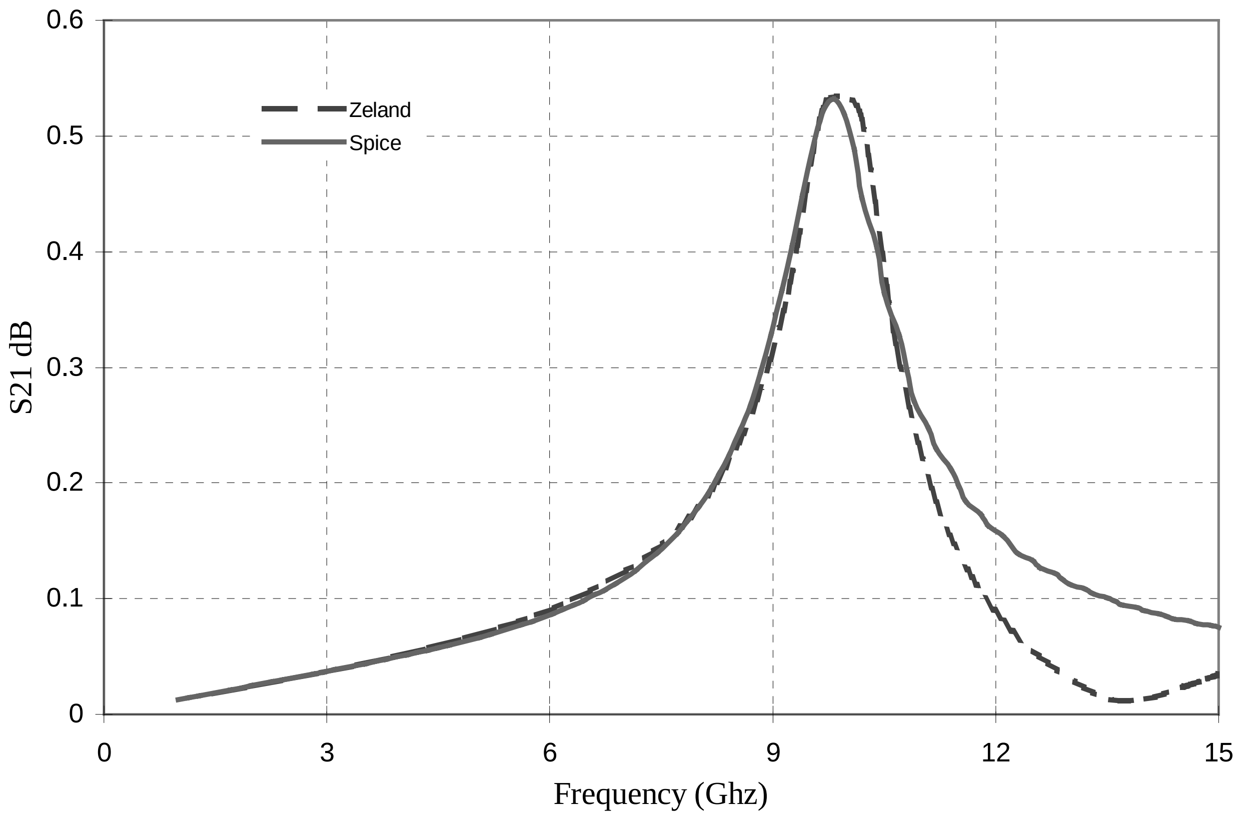


Fig 4.4 Pspice modeling for a transition of 0 mils overlap

As we can see from Figure (4.3), the transition region consists of three parts. The 1st part is a transmission line representing the coplaner line part, followed by the lumped elements model of the coupling region, followed by the other transmission line representing the center stripline part. It is worth noting that the lumped model of the coupling region takes the approximate form of a series L – C combination. At the lower frequencies the C part of this model dominates and hence the capacitive behavior of the gap. However, at the upper frequencies, the L dominates over the C resulting in an inductive coupling. The impedance of the L – C combination is high at both ends of the frequency range resulting in desired weak coupling to and from the stripline resonator to minimize the loading effect of the source and load side impedances.

The L- C combination, and hence the coupling region exhibit a low impedance around a certain frequency at which $\omega L = \frac{1}{\omega C}$. At this frequency and in its vicinity, the coupling reaches its peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value. In this frequency range, measurement of the dielectric properties looses its accuracy because the lowered Q values means inaccuracies in determining the resonant frequencies as well as great error in determining the Q_c and Q_d terms in equation (3.17).

In an attempt to remedy this increase coupling behavior, reactive tuning elements are sought to be added to the transition region. The goal is to add reactance(s) to tune out the low impedance behavior and weaken the coupling and hence the loading of the resonator section [32].

We found that we can improve the behavior of the gap and the overall resonator response at higher frequencies by adding a compensating shunt resonant branch as shown in Figures (4.6), (4.7), (4.8), and (4.9).

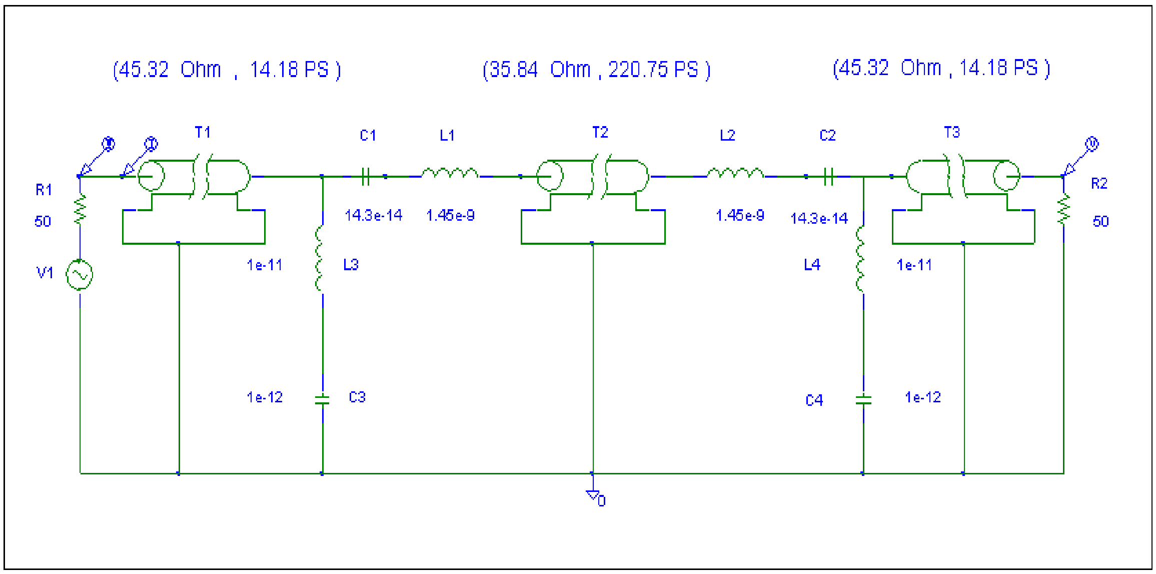


Fig 4.6 Overall Pspice model with compensating shunt branch

As we can see from the figures (4.7), (4.8), and (4.9), that there is a notice improvement in the transition and the overall stripline resonator frequency response after adding this compensating shunt branch to the Pspice model in our interesting frequency range (8 GHz to 12 GHz).

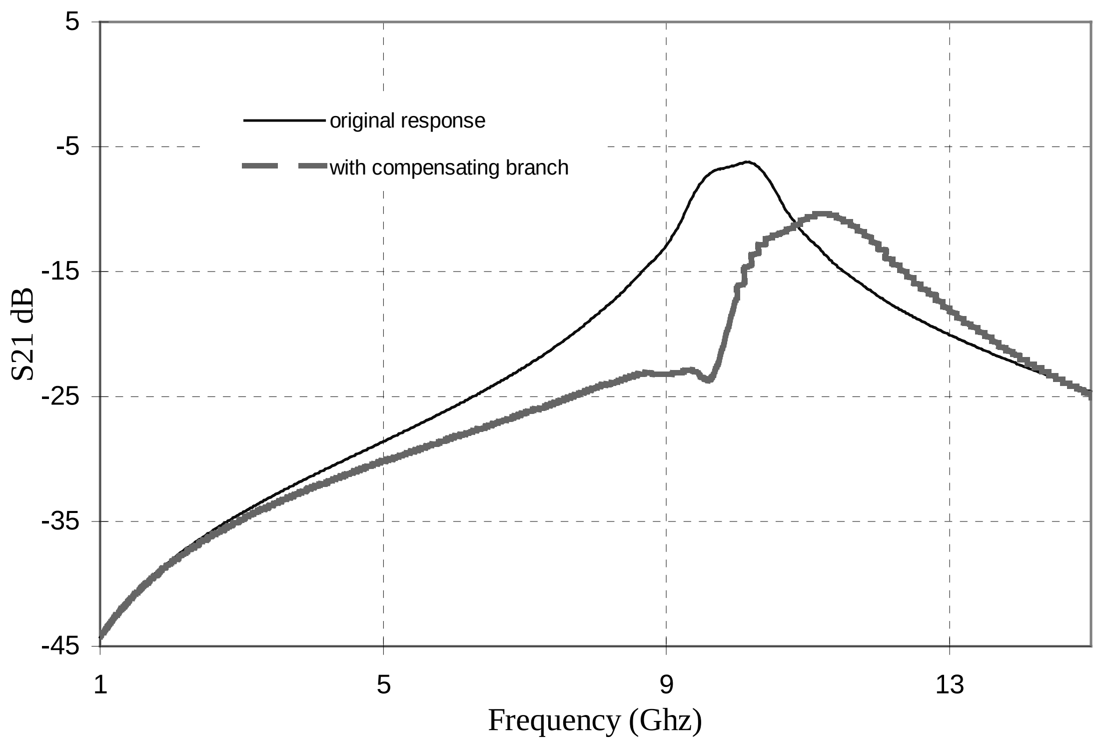


Fig 4.7 Transition response with shunt resonance branch overlap -40 mils

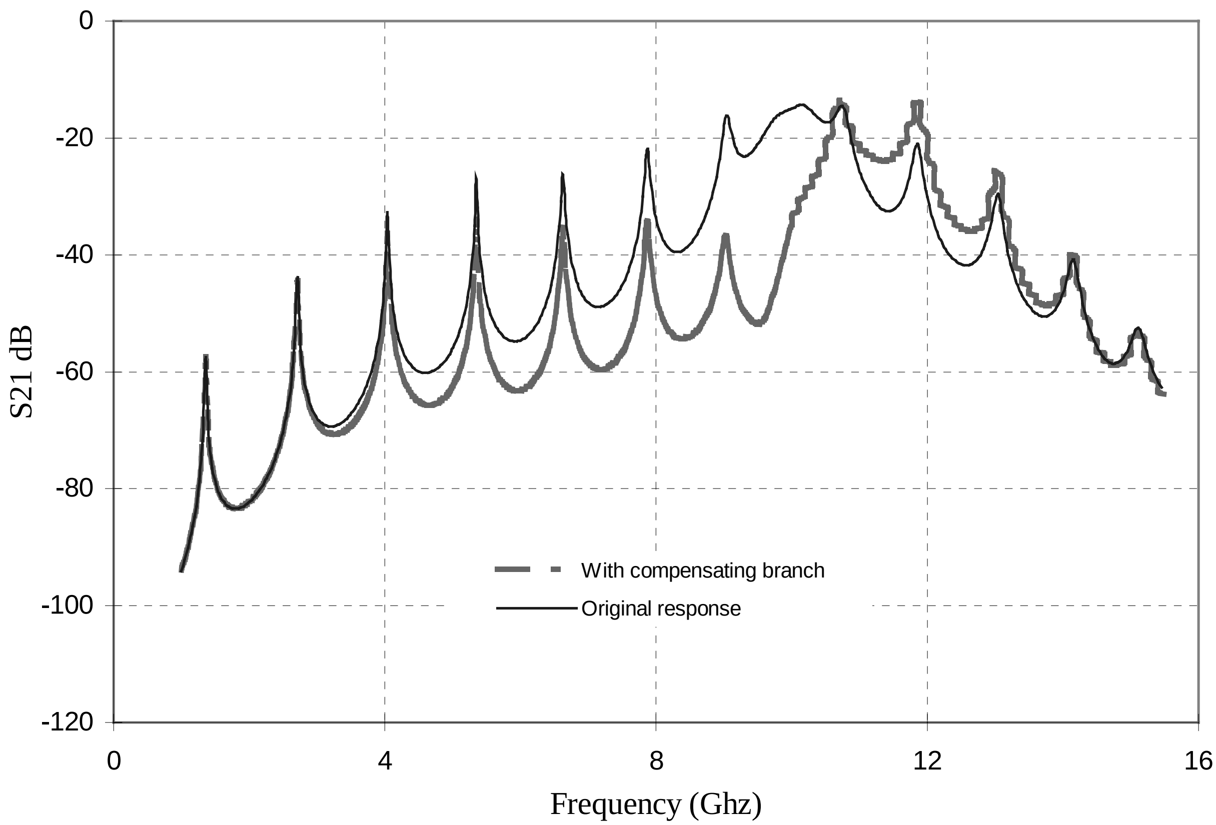


Fig 4.8 Overall response with shunt resonance branch: overlap –40mils

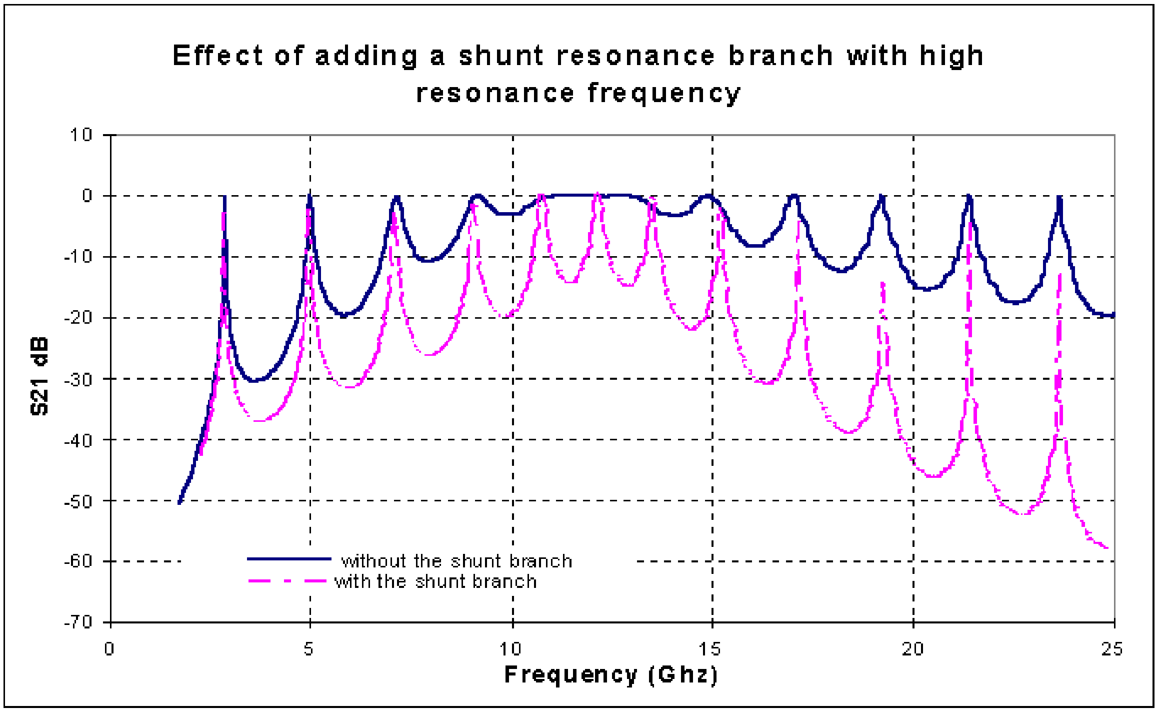


Fig 4.9 Overall response after adding a shunt resonance branch

In conclusion to this section, we can say from the lumped element model of the gap that, the gap behavior is not purely capacitive in the high frequency range, but it is more complex one. Also we can improve the transition and the overall stripline resonator frequency response in the high frequency range by adding a suitable compensating resonant shunt branch to our model of the gap.

Chapter 5

Problems and Optimum Designs of the CCSLR Structure

5.1 Introduction

Our problem, as we had mentioned before, is that, we can not get good values for Q using our stripline at the 8GHZ frequency and above. Therefore we can't accurately calculate the dielectric constant of the given material at this range of frequencies. So we have to look for a good design of the CCSLR to be able to get good resonance at frequencies higher than 8GHZ using the same material. The material used in our simulations has a dielectric constant $\in_r$ equal to 2.

The approach used in optimizing the design of the CCSLR will be based on trial and error. Intuitive designs will be simulated using the IE3Dsoftware and the results will be studied and analyzed. Modifications and changes will be added as necessary.

In order to avoid lengthy and extensive simulations of the entire structure each time a change is introduced, regional simulation will be used to study the performance of the resonator. In stead of performing one comprehensive simulation of the whole resonator, regional simulation of the coplanar section, the transition (gap) section, and the stripline section will be performed separately. A composite characteristics of the CCSLR is then obtained by combining individual regional characteristics as discussed in the following section.

5.2 Electromagnetic Simulation of the CCSLR Structure

The CCSLR structure shown in Figure (2-5) consists of coplaner line, stripline, and the transition region (gap) between the coplaner and the stripline in both sides. Due to the time that the electromagnetic simulation software IE3D takes in calculating the frequency response of this CCSLR in our high frequency range, and due to the large number of different designs we had, we have to devide this CCSLR to five different regions (Coplaner, Transition, stripline, Transition, and Coplaner) during our simulations. In all this simulations we run each region only one time. After simulating each region separately we have to collect all these results and calculate the over all response of the CCSLR. We used a MatLab program for collecting these results and calculating the over all response of the resonator, also to increase the number of data points to be able to get a fine graph of the S-parameters frequency by interpolating our results. In this program we load the output of the simulated region, this output includes both the magnitude and phase of the S-parameters of this region, and after that we calculate the S parameters from its magnitude and phase values according to these expressions.

S11= $|S11| * (\cos((\angle S11) * \pi \div 180) + i * \sin(\angle S11) * \pi \div 180))$

S12= $|S12| * (\cos((\angle S12) * \pi \div 180) + i * \sin(\angle S12) * \pi \div 180))$

S21= $|S21| * (\cos((\angle S21) * \pi \div 180) + i * \sin(\angle S21) * \pi \div 180))$

S22= $|S22| * (\cos((\angle S22) * \pi \div 180) + i * \sin(\angle S22) * \pi \div 180))$

Due to the symmetry of the coplaner region in both sides (S11= S22 , S12= S21), we load only the magnitude and phase of (S11 and S21) from the simulation results. The same is for the stripline, also we need to load the magnitude and phase of (S11 and S21) from the simulation results due to the symmetry in both sides and calculate the S-parameters from these two by the same set of equations.

Regarding to the transition regions we have two transition regions, one of them before the stripline and the other after it. For the fist one, we will load the resulting S parameters (S_{11}, S_{12}, S_{21}, S_{22}), magnitude and phase, of the simulated transition region and by the same way calculate the corresponding S- parameters according to the same equations. For the second transition region, we have to reverse these results due to the inversion in position in both the coplaner and the stripline, as follows:

S11 (2nd transition) = S22 (1st transition)

S12 (2nd transition) = S21 (1st transition)

S21 (2nd transition)= S12 (1st transition)

S22 (2nd transition) = S11 (1st transition)

To be able to get the overall response of the CCSLR (S-parameters) within the specified frequency range, we will transfer the S matrix for each region to their corresponding T matrix to be able to multiply all the five region's T matrices together. After T matrices multiplication of all regions, we can transform the overall T matrix of the CCSLR to the overall S matrix according to these relations between S and T matrices:

T11 = 1 / S21

T12 = - S22 / S21

T21 = S11 / S21

T22 = S12 - (S11 * S22) / S21

If :

Ta .... is the T matrix of the 1st coplaner

Tb .... is the T matrix of the 1st transition

Tc .... is the T matrix of the stripline

Td .... is the T matrix of the 2^{nd} transition

Ta .... is the T matrix of the 2^{nd} coplaner

The over all T matrix of the S.L.R is given by

T (overall) = Ta*Tb*Tc*Td*Ta

The over all S matrix of the S.L.R is given by

S11(overall) = T21 / T11

S12(overall) = T22 - (T21 * T12) / T11

S21(overall) = 1 / T11

S22(overall) = - T12 / T11

So using this MatLab program, we can calculate the S-parameters of the transition region (gap) and at the same time the overall S-parameter of the CCSLR for any design we have.

5.3 Proper Design using Optimized Dimensions

The first set of designs we will start with depend on the change in dimensions of the CCSLR elements (coplanar line, stripline, and transition regions). We will start our designs by changing the dimensions of the coplanar as shown in Figure (5-1).

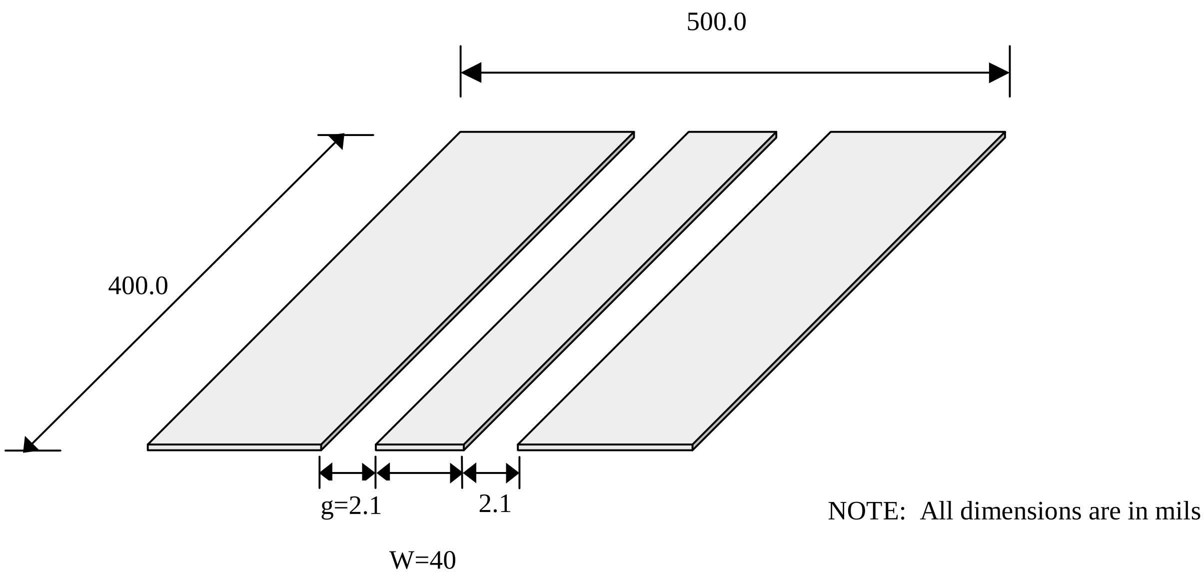


Fig 5.1 Coplaner Line Dimensions

The Z coordinate of the coplanar is equal to 28.2 mil. We will call the coplaner with these dimensions as coplaner 1. We will start to change the *w* and *g* dimensions of the coplanar line according to Table (5-1).

Table 5.1Coplaner Line Dimensions

Coplaner Line	**W (mil)**	**g (mil)**	**Zo (Ω)**
1	40	2.10	50.00
2	50	3.38	50.01
3	60	5.40	50.00
4	80	16.00	50.04
5	100	20.00	44.47
6	30	1.30	49.98
7	20	1.00	53.05
8	10	0.40	51.70

After these coplanar designs we will start to change the dimensions of the stripline according to table (5.2). The original design dimensions of the stripline is as shown in Figure (5.2). The Z coordinate of the stripline is equal to Z=14.1 mil.

Fig 5.2 Stripline Dimensions

Simulation of the full length of the SLR region proved to be extensive and time consuming. An alternate approach to the full simulation was used to avoid this difficulty. Instead of simulating the full length of 2540 mils a much shorter length of 54 mil was simulated. The full characteristics of the 2540mils can be extrapolated using the analytical model for a uniform transmission line.

Table 5.2 Stripline Dimensions

Stripline	W (mil)	L (mil)	Zo (Ω)
1	40	54	35.84
2	50	54	30.10
3	60	54	25.95
4	25	54	50.20
5	20	54	57.97
6	15	54	68.68
7	10	54	84.69

Next, we will turn to the transition region (gap) design.

Table 5.3 Transition Region Dimensions

Transition Region	Overlap (mil)	Coplaner Length (mil)	Stripline Length (mil)
1	0	190	230
2	10	190	240
3	20	190	250
4	40	190	270
5	100	190	330
6	150	190	380
7	190	190	420
8	-10	190	220
9	-20	190	210
10	-40	190	190
11	-100	190	130
12	-150	190	80
13	-190	190	40

We have now eight designs for coplanar line, seven designs for stripline, and thirteen designs for the transitions region (gap). By simulating the all designs of each section separately using the (IE3D) software, we can get their S-parameters in magnitude and phase. Using the S-parameter files of these sections in our MatLab program, we can calculate the overall S-parameters for all the possible combinations between these sections (coplaner, transition, and stripline). For simplicity during the comparison between the original design of the CCSLR and all the other combinations, we will name the output file of the MatLab program for each combination as a three digits number. The first digit represents the coplaner design number, the second digit represents the transition design number, and the third digit represents the stripline design number. As an example, the file name (1 2 3) means, the output file of the CCSLR design which has the combination of the coplanar design number 1, transition design number 2, and stripline design number 3. Using these output files we can compare between the different designs and according to these comparisons, we can choose the best design to use for our material characterization.

In the next step, we will compare the transition response and the overall response of the original design of the CCSLR with the all other possible combinations. The original design of the CCSLR has the following dimensions:

Coplaner Dimensions:

W = 40 mil

g = 2.12 mil

Zo = 50.00 ohm

$\varepsilon_r = 2$

Stripline Dimensions:

W = 50 mil

Zo = 30.1 ohm

Transition Dimensions:

It has 20 mil overlap between the coplaner and the stripline

coplaner length = 190 mil

stripline length = 250 mil

Using the MatLab program, We simulated all the possible designs of the CCSLR by trying all the combinations between the different dimensions of the coplaner line, the transition region, and the stripline. We will present here a sample of these comparisons between the original design and two of the used combinations. Some of these comparisons are presented in the appendix

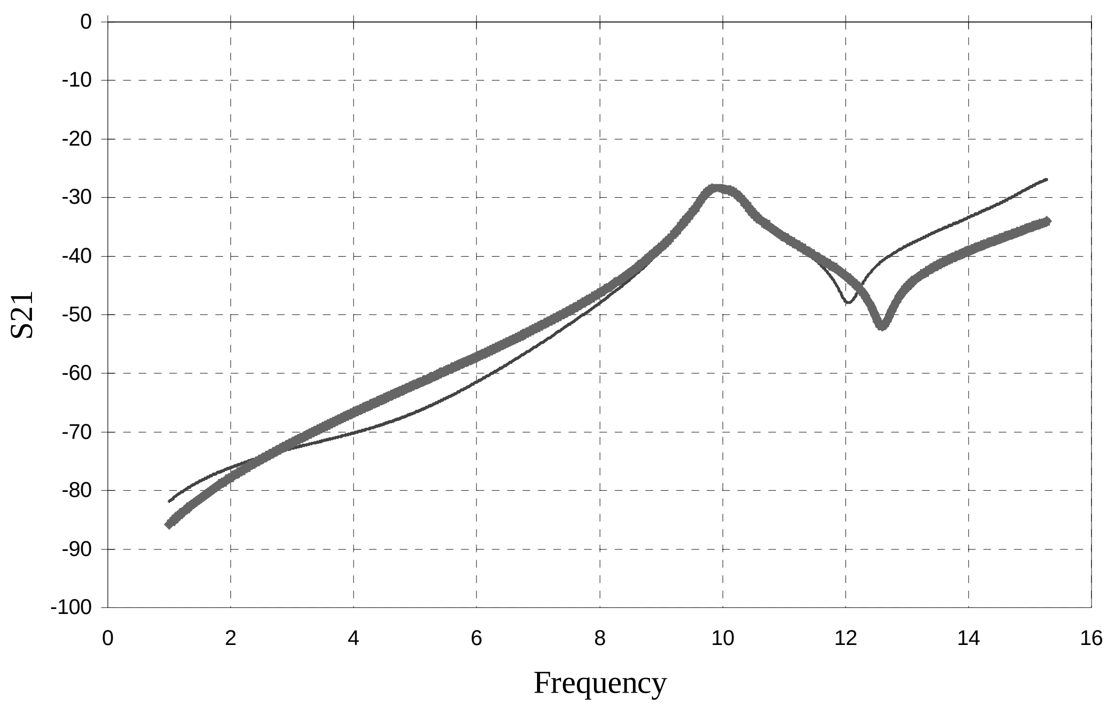


Fig 5.3 Comparison between S21 of the original transition region with different designs (132 VS 114)

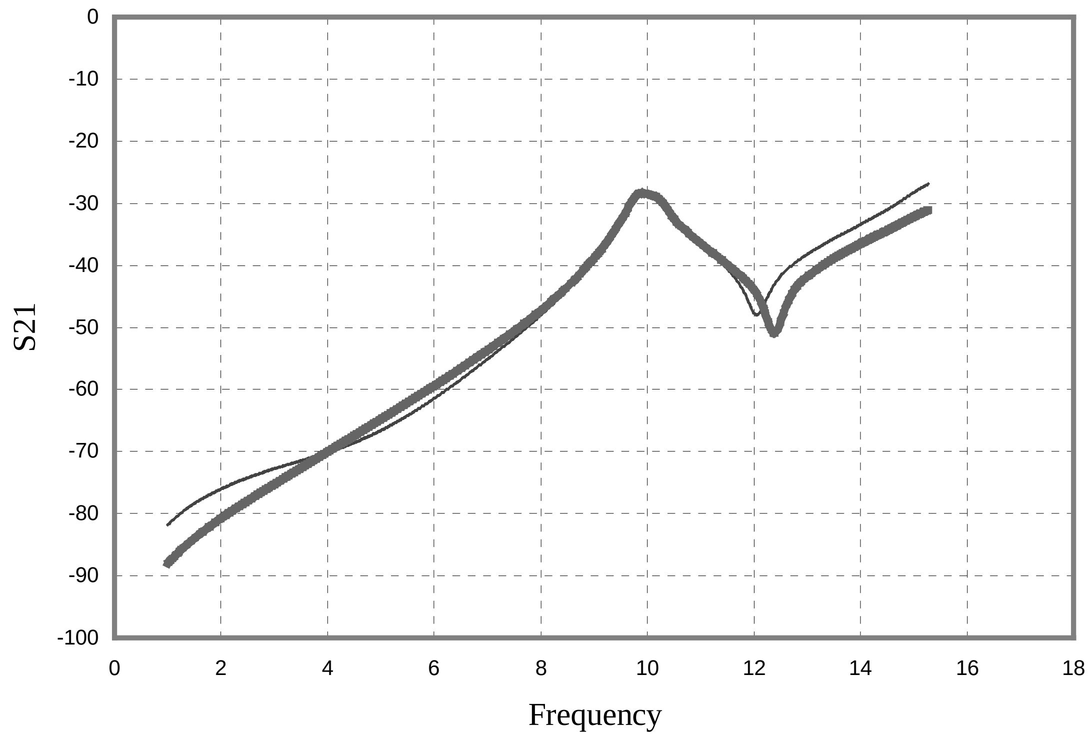


Fig 5.4 Comparison between S21 of the original transition region with different designs (132 VS 124)

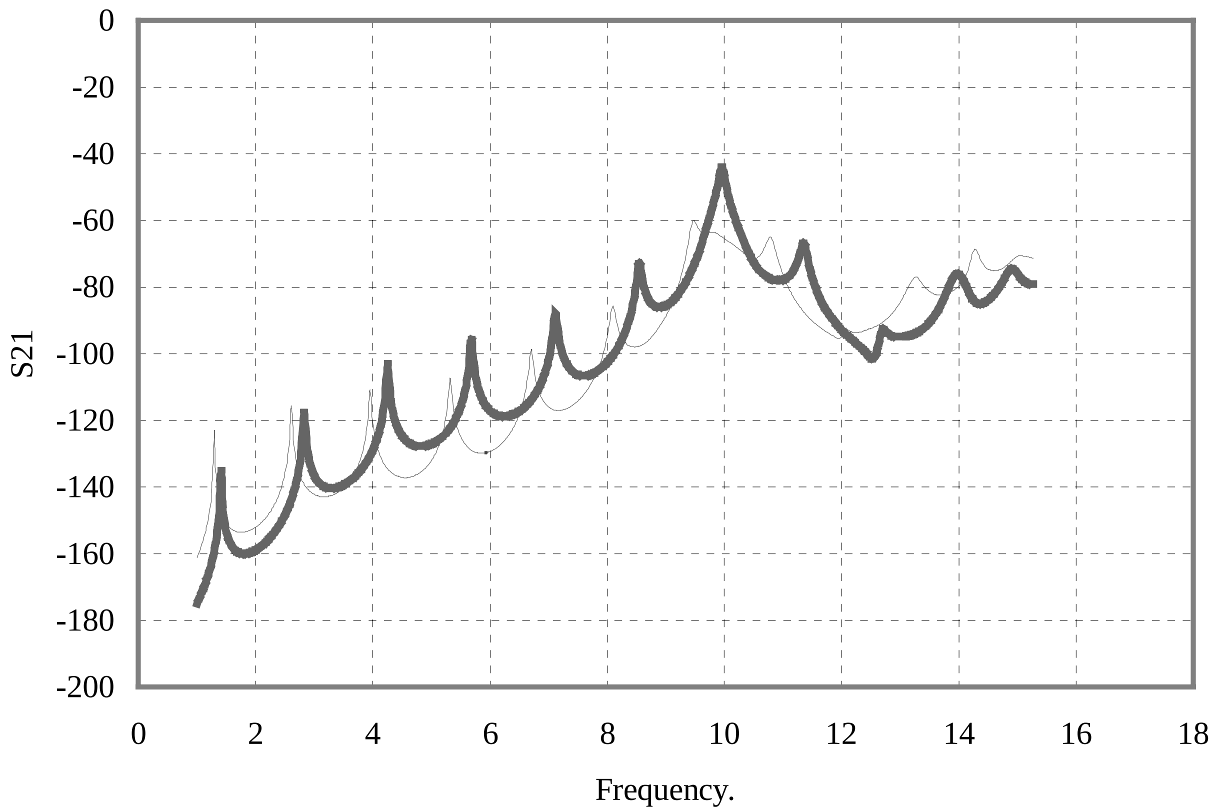


Fig 5.5 Comparison between the overall S21 of the original design with different designs (132 VS 114)

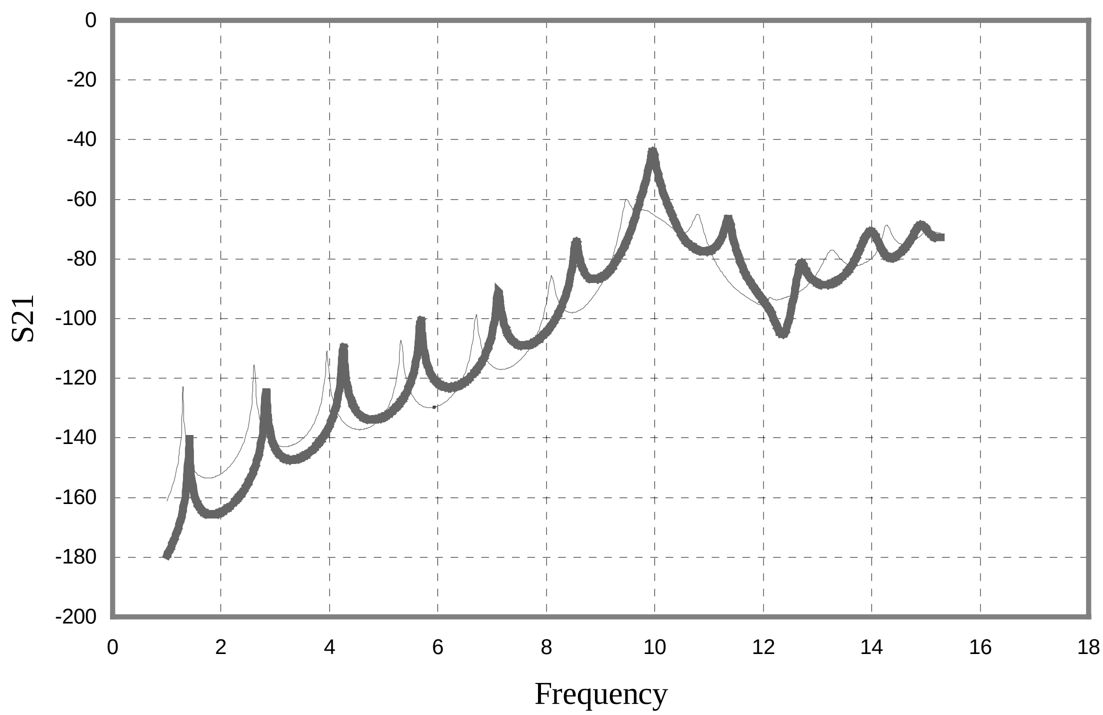


Fig 5.6 Comparison between the overall S21 of the original design with different designs (132 VS 124)

From the overall comparison between the original design and all the other possible combinations, we can see that the best design here is the design which has (Coplaner 1, Transition 2 , Stripline 4), i.e. which has these dimensions:

Coplaner Dimensions:

W = 40 mil
g = 2.12 mil
Z0 = 50.00 ohm
$\varepsilon_r = 2$

Stripline Dimensions:

W = 25 mil
Z0 = 50.2 ohm

Transition Dimensions:

It has 10 mil overlap between the coplaner and the stripline
coplaner length =190 mil
stripline length = 240 mil

5.4 Proper Design using Via Technique

The Pspice simulation of chapter 4 revealed that an additional shunt LC can be designed to improve the gap performance in the CCSLR structure. This can be realized by introducing a vertical stub to either of the two gap conductors. The stub would bridge part of the vertical gap without shorting to the other conductor.

(a) CCSLR transition region (gap). (b) Via augmented transition region

Fig 5.7 Comparison between the transition region of the CCSLR before and after adding via .

The conductor vertical stub will be refereed to as via in this work since it would be fabricated using the typical via fabricated methods. Figure (5.8) demonstrate the concept of the added conductor stub and how the shunt LC equivalence is introduced. The inductance introduced by via would depend on its cross sectional dimensions as well as its height. The capacitance component results from the surface area of via section and its relative position with respect to the ground conductors. The choice of the via being attached to the coplaner line rather than attaching it to the stripline section is to maintain the same length of the stripline resonator section.

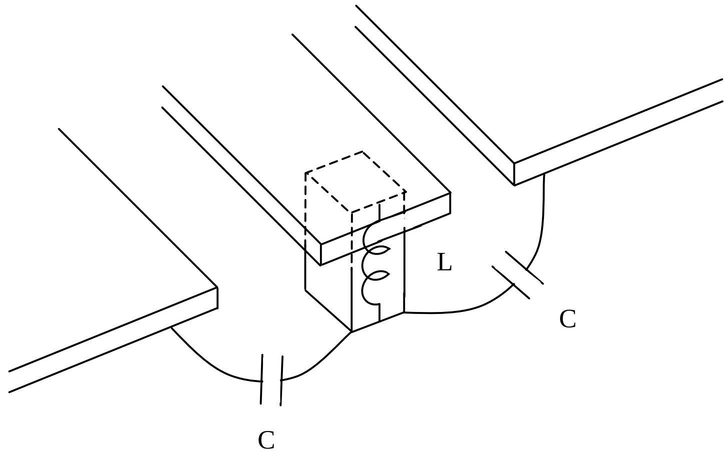


Fig 5.8 The coplaner line with the conductor stub

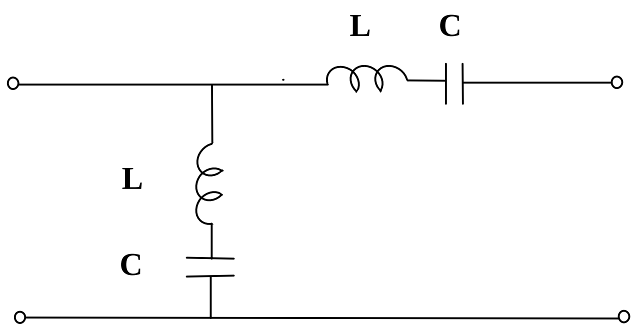


Fig 5.9 The over all lumped element model of the gap after adding the conductor stub

As discussed above controlling the dimensions of the via results in changing both L and C simultaneously. In order to increase the design flexibility to allow a separate control for the C component, an additional plate is added to the bottom of the stub. Figure (5.10) demonstrates the addition of this plate.

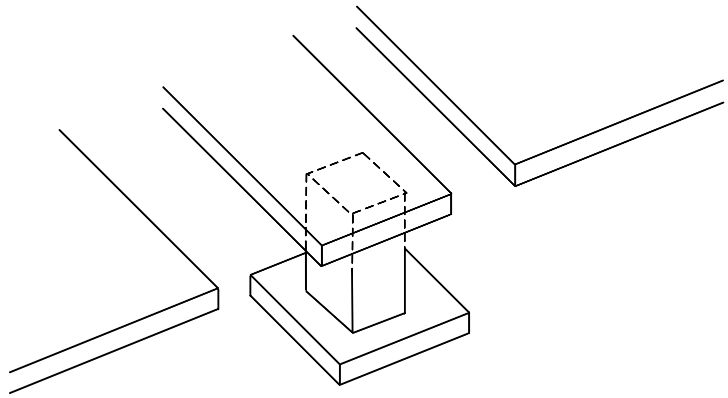


Fig 5.10 The additional plate at the bottom of the stub to flexibly control the capacitance component

In this section we will compare the frequency response of the original design with the new one after adding the via. In this comparison we will use different via dimensions and also; as we had mentioned before; we will add in some simulations a copper plate to the bottom of this via with different dimensions to give more flexibility in controlling the capacitance component.

We will start by simulating the transition region and the overall coplaner coupled stripline resonator without using the via and we will call this design the original design. This design has the same dimension as we used before in the previous chapters. Simulation of the transition region with different via and plate dimensions were made. Also, we had simulation of the over all coplaner coupled stripline resonator with the same via and plate dimensions. Due to the large number of the simulated designs and for the comparison purposes, we named these new designs according to the via and the plate dimensions as shown below in Table (5.4).

Table 5.4 Sample of the used new designs names

Name of the design	Via Dimensions (20 mil x 20 mil x h)	Copper Plate Surface area (as multiple of the via surface area)
Via (1wp1)	(20 mil x 20 mil x 1)	Same surface area
Via (2wp1)	(20 mil x 20 mil x 2)	Same surface area
Via (4wp1)	(20 mil x 20 mil x 4)	Same surface area
Via (8wp1)	(20 mil x 20 mil x 8)	Same surface area
Via (1wp1)	(20 mil x 20 mil x 1)	Same surface area
Via (1wp2)	(20 mil x 20 mil x 2)	Double the surface area
Via (1wp3)	(20 mil x 20 mil x 4)	Triple the surface area
Via (1wp4)	(20 mil x 20 mil x 8)	Four times the surface area

Simulations for the transition region and the overall coplaner coupled stripline resonator after adding the via with and without copper plate with different dimensions has been made. In some of these simulations, we used two adjacent via with the same dimensions in the design. We will add to the name of this design the letter d, which means we doubled the via in this design. For example the design (d3wp4) is the same as the design (3wp4) except for we doubled the via number 3.

To be able to illustrate the improvement in the frequency response of the transition region as well as the overall coplaner coupled stripline resonator, after adding the via with and without copper plate, comparisons between the S_{21} in all cases are shown below in the next set of figures.

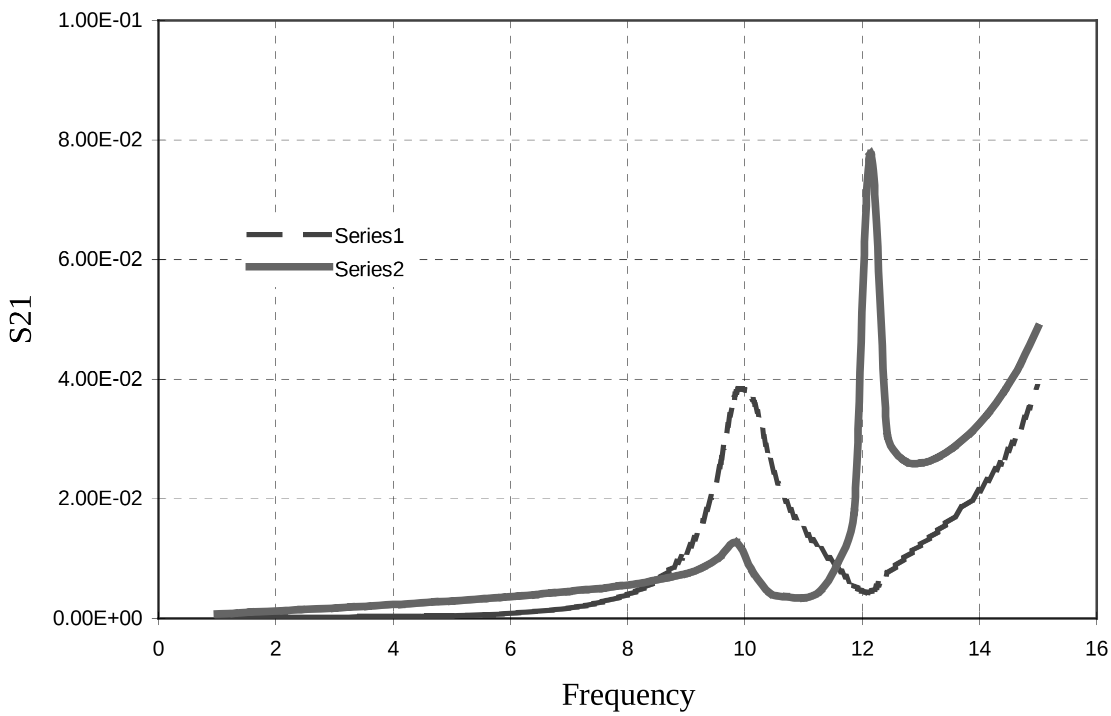


Fig 5.11 Transition region comparison between the original design and the design with via (3wp4)

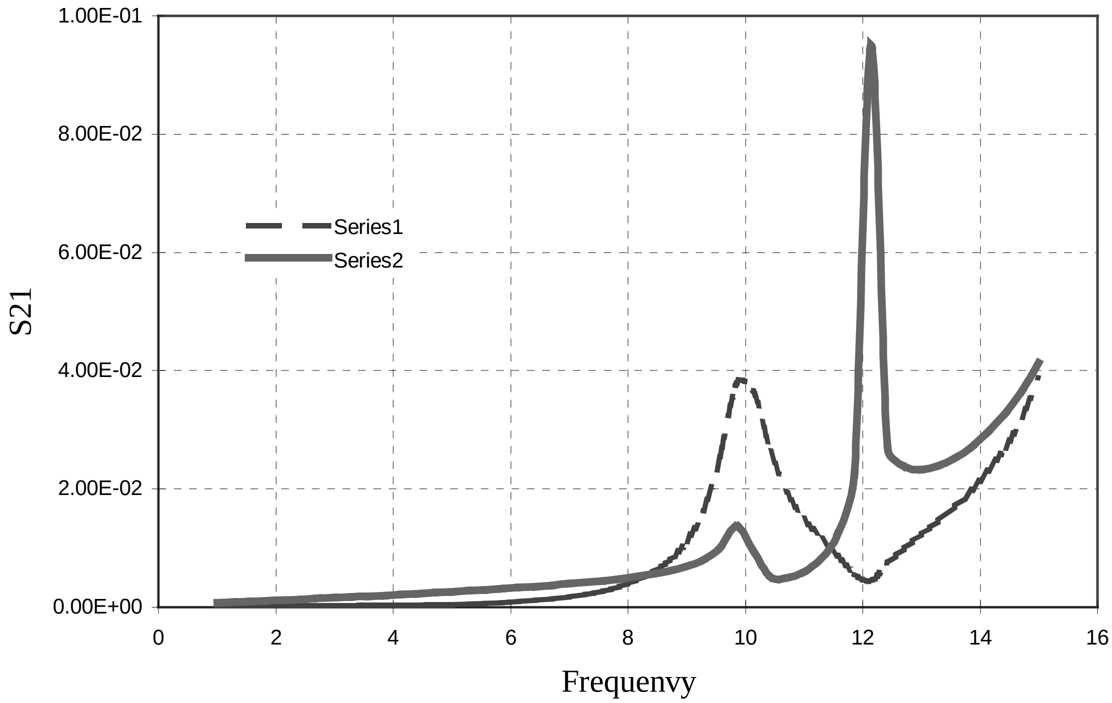


Fig 5.12 Transition region comparison between the original design and the design with via (4wp4)

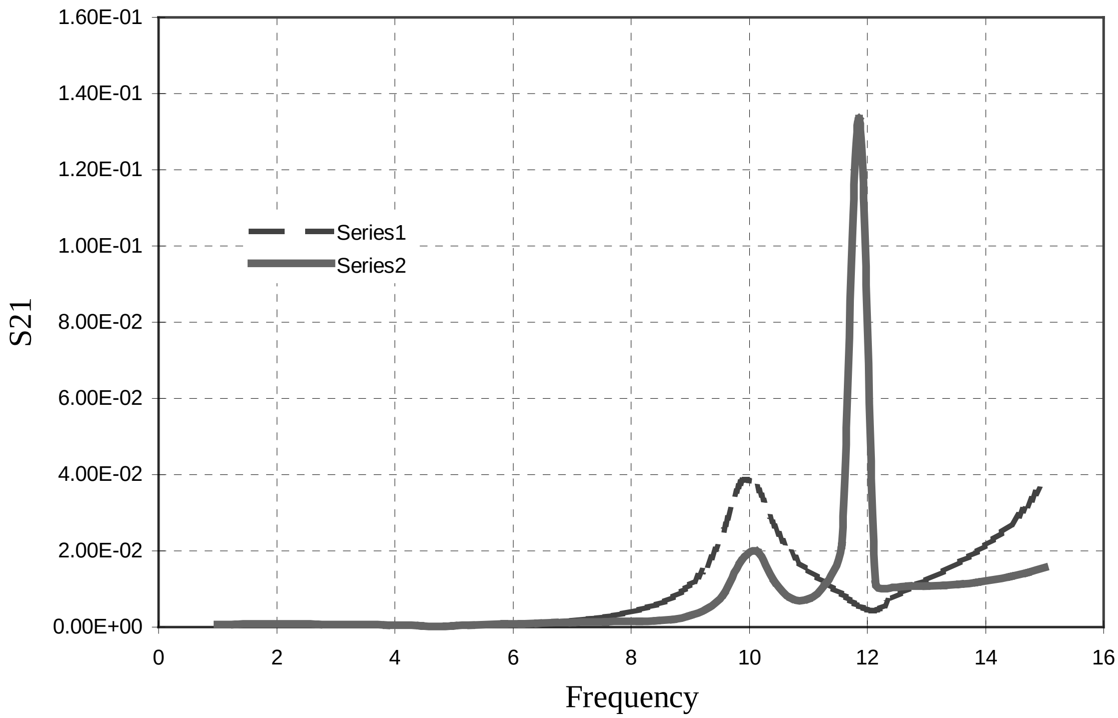


Fig 5.13 Transition region comparison between the original design and the design with via (4wp8)

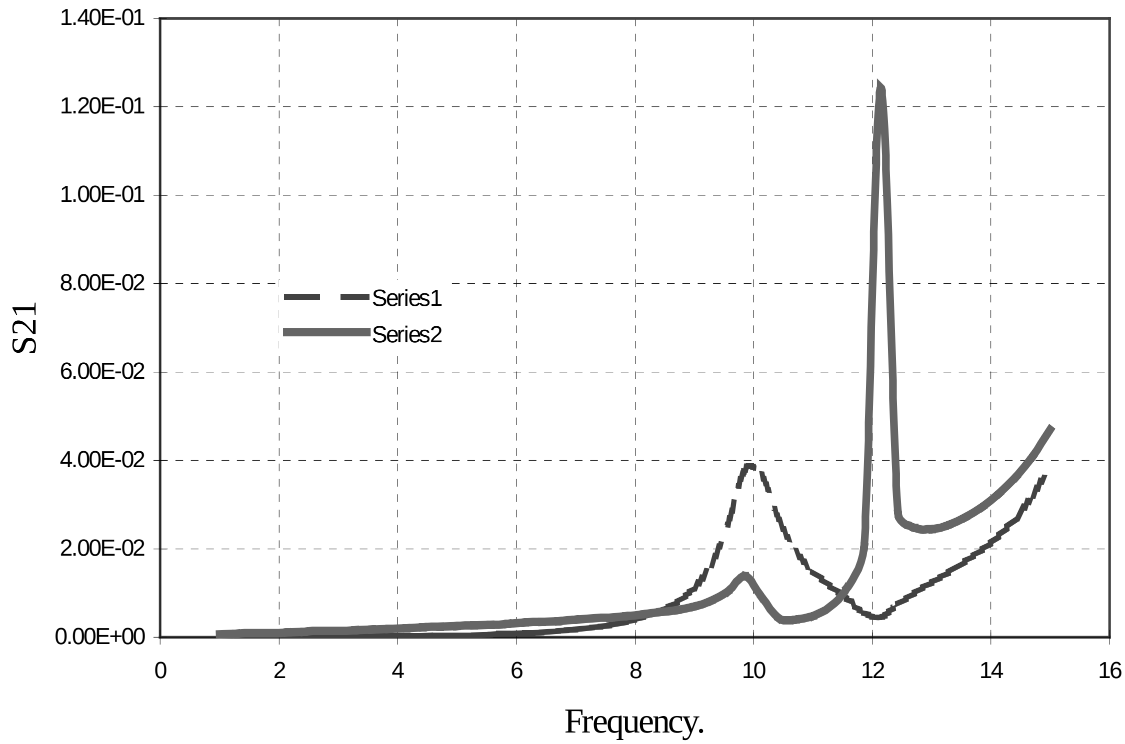


Fig 5.14 Transition region comparison between the original design and the design with via (d3wp4)

As we had mentioned before, we loose our sharp resonance frequencies in the high frequency range due to the low Q values of these resonances. This frequency range is from 8 GHz to 12 GHz. In the last compressions between the S_{21} for the transition region of the original design and the S_{21} of the transition region using the via, we can see the improvement in the frequency response of the transition region after using the via. Also, we can see the effect of the via and the copper plate dimensions on the frequency response of the transition region.

In the next set of figures, we will see the effect of using the via in the overall frequency response of the coplaner coupled stripline resonator. This can be done by the comparison between the S_{21} of the original design and the S_{21} of the new designs using different via and copper plate dimensions.

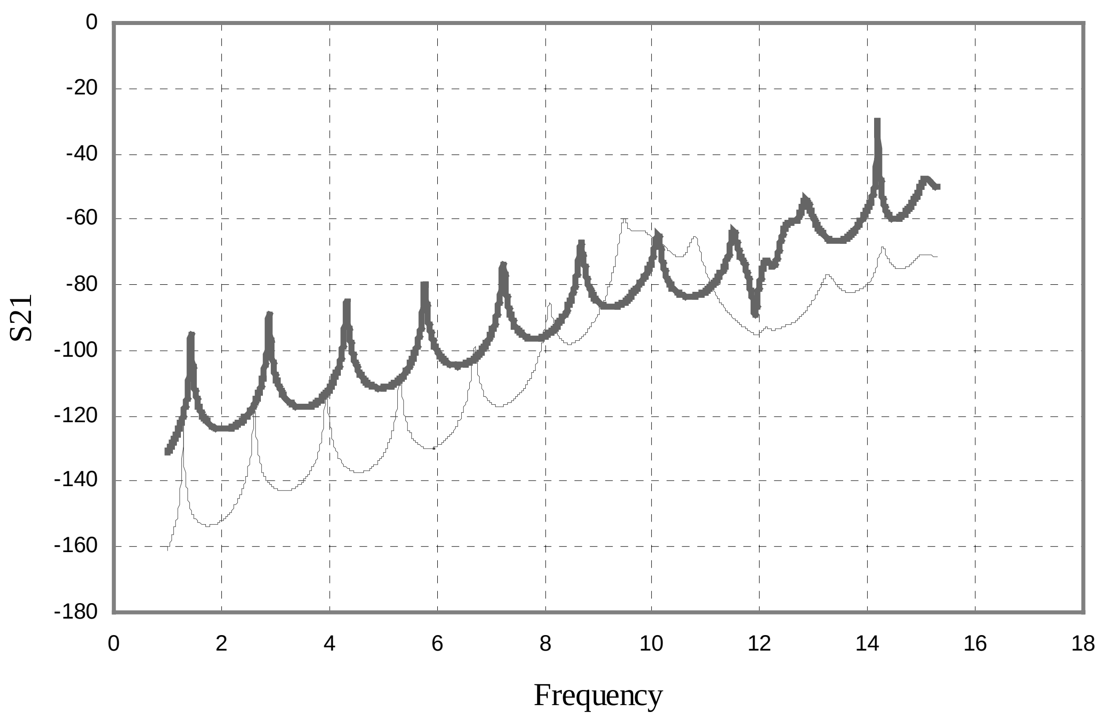


Fig 5.15 Comparison between the overall S21 for the original design and the design with via (1wp4) using the stripline 5

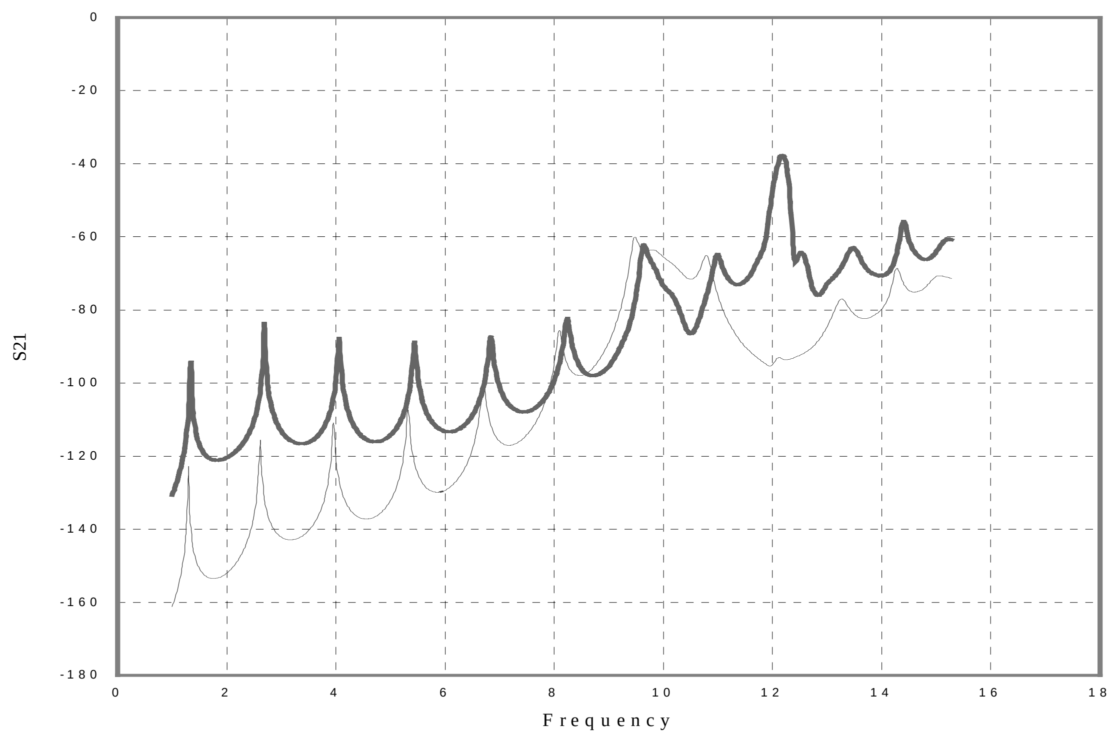


Fig 5.16 Comparison between the overall S21 for the original design and the design with via (4wp2)

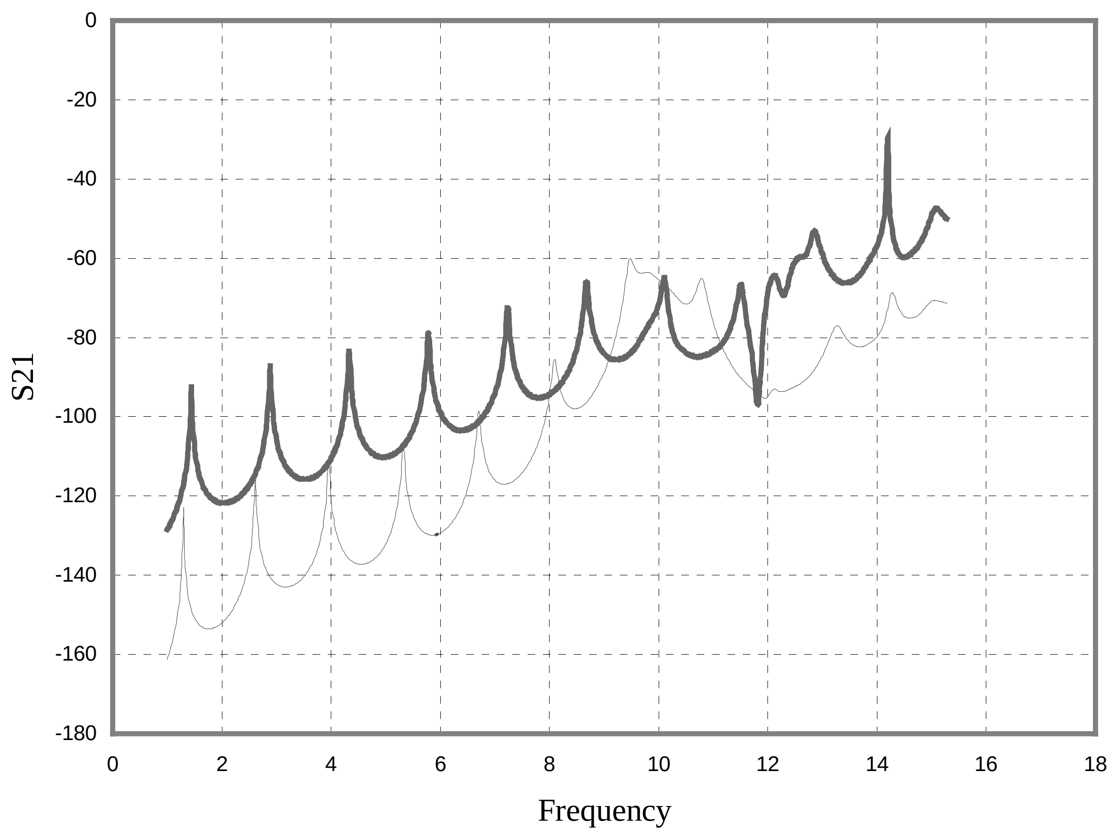


Fig 5.17 Comparison between the overall S21 for the original design and the design with via (d1wp3) using the stripline 5

From the last comparison, we can illustrate the improvement in the frequency response of the coplaner coupled stripline resonator after using the via. We noticed that the Q value of the resonance frequency is increased in our interesting frequency range (from 8 GHz to 12 GHz). This improvement in the Q value and in the resonance frequencies will increase the accuracy of the dielectric material characterization in this frequency range.

5.5 Overall Comparison

Now we can compare between the original design of the coplaner coupled stripline resonator and the all other new designs we had mentioned in this chapter. From these comparisons, we can determine which design is more suitable for the modification of our used design of the coplaner coupled stripline resonator in dielectric material characterization.

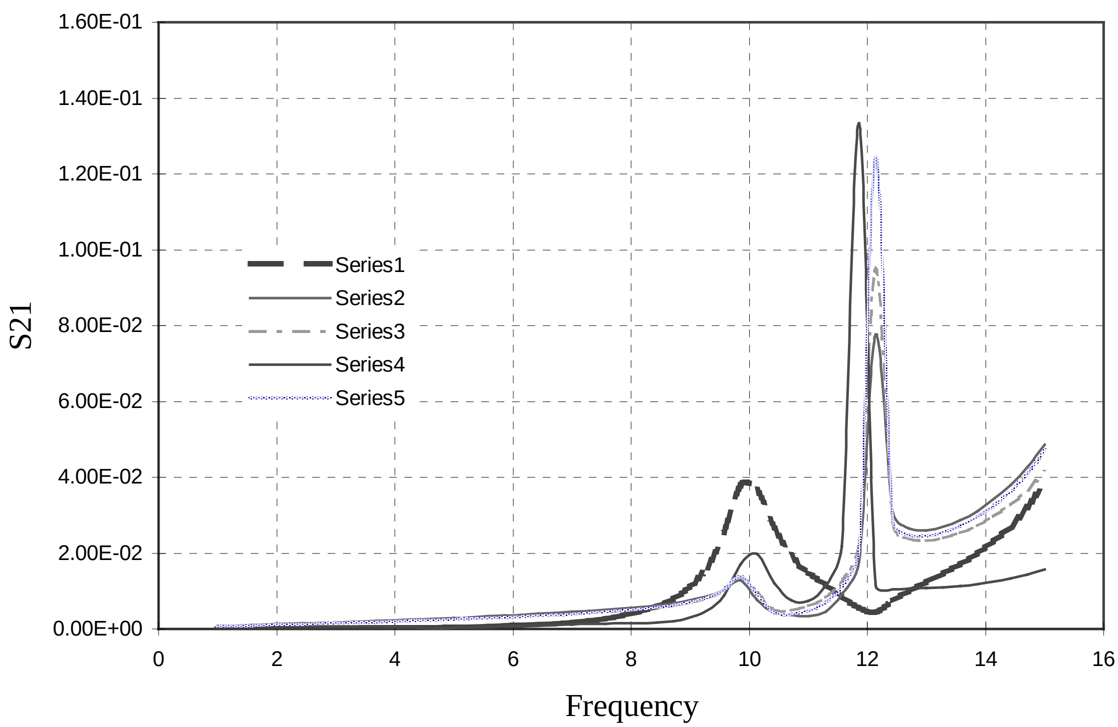


Fig 5.18 Transition region comparison between the original design and the design with via (3,4,8wp4,d3wp4)

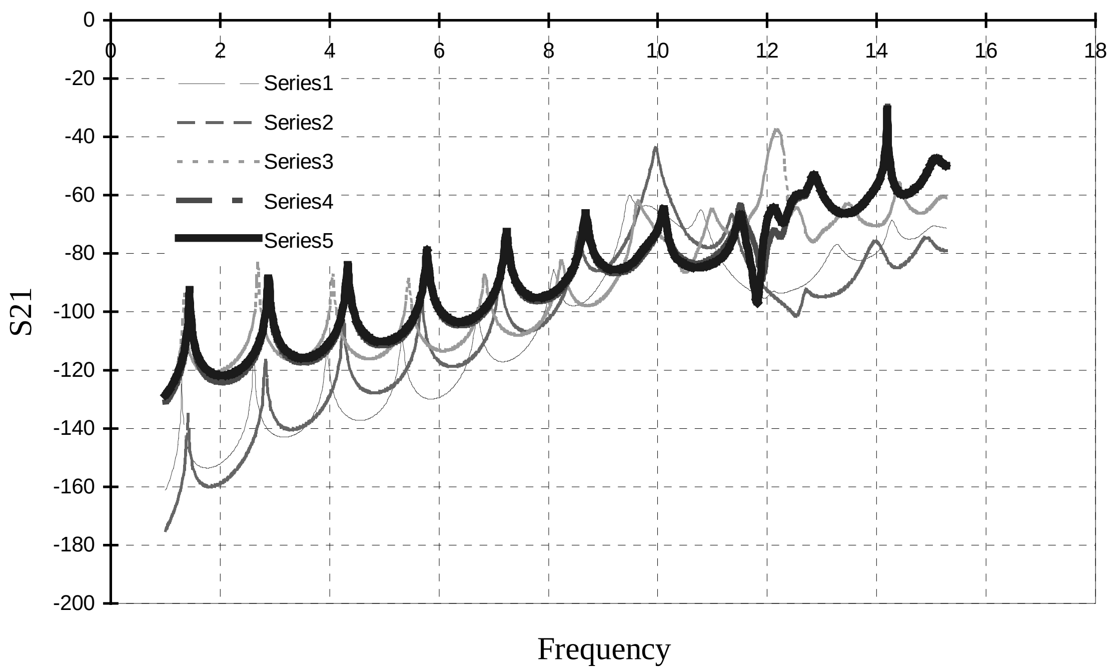


Fig 5.19 Comparison between the overall S21 for the original design and all the others (114, 4wp2), (1wp4, d1wp3) using the stripline 5

As depicted from figures (5.18), and (5.19), that using via with copper plate in the design of the CCSLR is improving the frequency performance of both the transition region and the overall CCSLR in our interesting frequency range. This improvement in the frequency response is due to the increase in the Q value of the resonance frequencies in this frequency range. In other words, increase in the reactance of the transition region of the coplaner coupled stripline resonator due to the existence of the via with its copper plate instead of the via. We can control the values of these reactance according to the via height and its copper plate dimensions.

In addition, we can see from these comparisons that, by changing the via dimensions as well as its copper plate dimensions, we can control the frequency range of the improvement of the used coplaner coupled stripline resonator. This means, according to the used coplaner coupled stripline resonator dimensions, we can choose the suitable via and its copper plate dimensions, which will help to improve the frequency response of this coplaner coupled stripline resonator in its improper frequency range. Therefore, we can use this idea to construct different designs for the coplaner coupled stripline resonator using different via and copper plate dimensions. Each one of these designs is suitable for certain frequency range. Using the suitable combination of these different designs, we can accurately characterize the used dielectric material.

Chapter 6

Study and Analysis in the Effect of the Via on the Resonance Frequency of the CCSLR

6.1 Introduction

As we recall, the original coplaner coupled stripline resonator design failed to produce sharp resonances at high frequencies to use in the dielectric material characterization. This is because the reactance of the gap in the transition region dropped at the high frequencies, which resulted in a reduced quality factor value Q.

$$Q = \frac{X}{R}$$

This means at high frequency range, we have a low reactance value, which gives a low Q value, so we do not have enough number of sharp resonance to use in the dielectric constant calculations.

By using the via in the design of the coplaner coupled stripline resonator, we noticed that there is an improvement in the quality of the resonance frequencies, especially at the high frequency range. Although, we noticed that there is a slight shift between the resonance frequencies of the original design and the one with the via**.**

In the frist section of this chapter, we will explain the reasons of the improvement in the quality factor Q at the high frequency range after using the via. This can be done by simulating a simple lumped elements model of the transition region of the coplaner coupled stripline resonator using IE3D Zeland simulation software. By using this model, and by the impedance calculations for this model verses frequency, we can recognize the reactance behavior of the transition region along our frequency range, which will give us an explanation of this phenomena.

In the second section, we will discuss the resonance frequency shift problem we noticed while using this via between the coplaner line and the stripline in the design of the coplaner coupled stripline technique. While comparing between the S_{21} of the original design and the S_{21} of the new design with the via, we noticed that there is a slight shift in the resonance frequencies between both of them.

To be able to see how far this shift will affect on the accuracy of the dielectric material characterization; spiacially the relative permetivitty calculations; we will present a complete addresses and analysis to this phenomenon. This can be done firest, by discussing the reasons of this resonance frequencies shift and how we can minimize it. Second, by calculating how far is this shift from the original ones and what is the relation between this shift and the via and the copper plate dimensions. Third, by comparing the relative permitivitty results in both cases. Finally by finding out what is the possible solution to this problem.

6.2 Reactance performance of the Transition RegionVersus Frequency

To be able to get an accurate estimation of the dielectric constant value of the material using the coplaner coupled stripline resonator technique, we have to have an enough number of sharp resonance frequencies, which will be used in the calculations of this dielectric constant of the used material.

In the original design of the coplaner coupled stripline resonator technique,we can't get enough number of clear sharp resonance frequencies, specially at the high frequency range (in our case after 8GHz). This because the low quality factor value Q of this resonance frequencies (after the 8GHz). This can be exlaned using the lumped element model of the coupling region, whic takes the approximate form of a series L – C combination. At the lower frequencies the C part of this model dominates and hence the capacitive behavior of the gap. However, at the upper frequencies, the L dominates over the C resulting in an inductive coupling. The L- C combination, and hence the coupling region exhibit a low impedance around a certain frequency at which $\omega L = \frac{1}{\omega C}$. At this frequency and in its vicinity, the coupling reaches it's peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value.

By using the via between the stripline and the coplaner line in our design, we had an improvement in the frequency response of the coplaner coupled stripline resonator. This improvement can be depicted from the increase in the number of sharp resonance frequencies and also from the extension of the frequency range, which has this sharp resonance (from 8 GHz to 11.5 GHz) as shown in Figure 6.1. Due to this increase of the number of resonance and the extension of our frequency range, we can get more accurate results from the calculations of the dielectric constant of the material used in this coplaner coupled stripline resonator .

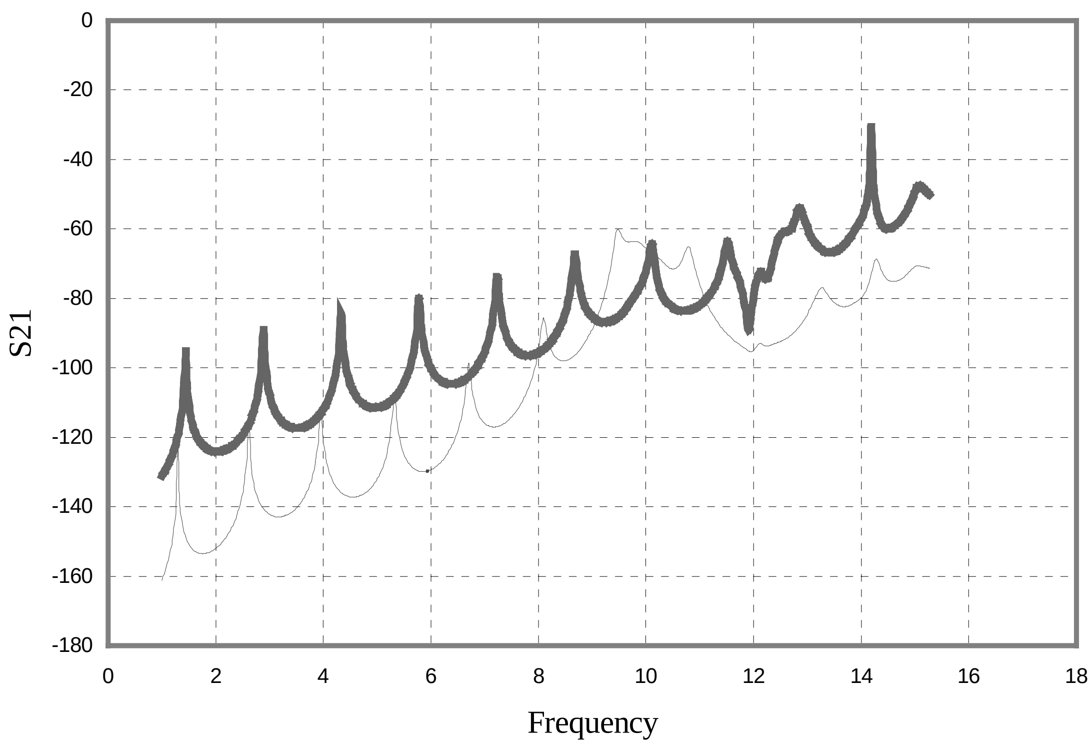


Fig 6.1 The improvement in the resonance frequencies after using the via in the design of the coplaner coupled stripline resonator

To explain the reason of this improvement in the coplaner coupled stripline resonator performance after using the via between the stripline and the coplaner line, we need to get the lumped element model of the transition region affter adding the via. Using the IE3D Zeland simulation software we simulate our transition region along our frequency range (from 1GHz to 15GHz), and due to the limitation in the software modiling, we were able to get a simple LRC lumped element model for the transition region as shown in Figure (6.2).

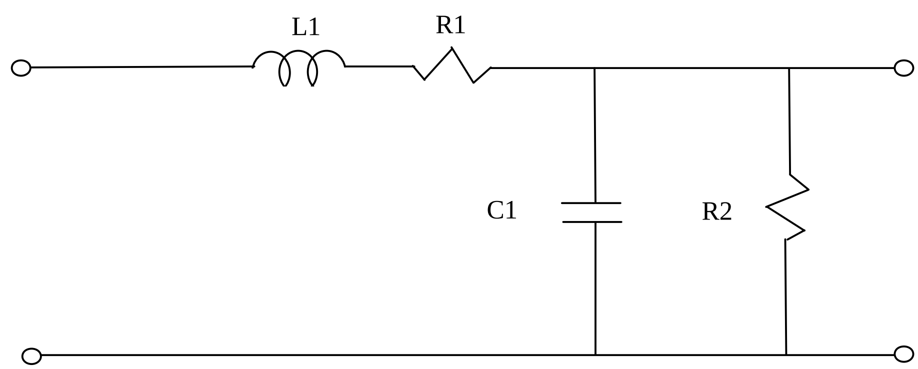


Fig 6.2 Simplified lumped element model for the transition region with via

The values of these lumped elements (R1, L1, C1 and R2) are varying along with the frequency and also depends on the via dimensions. From the calculations of Zc and Zl along our frequency range (1 GHz to 15 GHz) and by using different via dimensions we found that, the values of ZL and ZC are increasing with the increase of the via dimensions as the frequency increase. We will use in this set of simulations three different via dimensions as shown in Table (6.1).

Table 6.1 Different via dimensions used in Zl and Zc simulations

Via Name	Via Dimesions	Via hight
Via 1	1 mil by 1 mil	10 mil
Via 2	2 mil by 2 mil	10 mil
Via3	4 mil by 4 mil	10 mil

Using these different via in the simulation of the transition region and from the calcutaion of the ZL and ZC of the simplified lumbed element of this transition region, we noticed that , the values of both ZL and ZC are increasing with the increase of the via dimensions with the increse of the frequency as shown in the next set of figues.

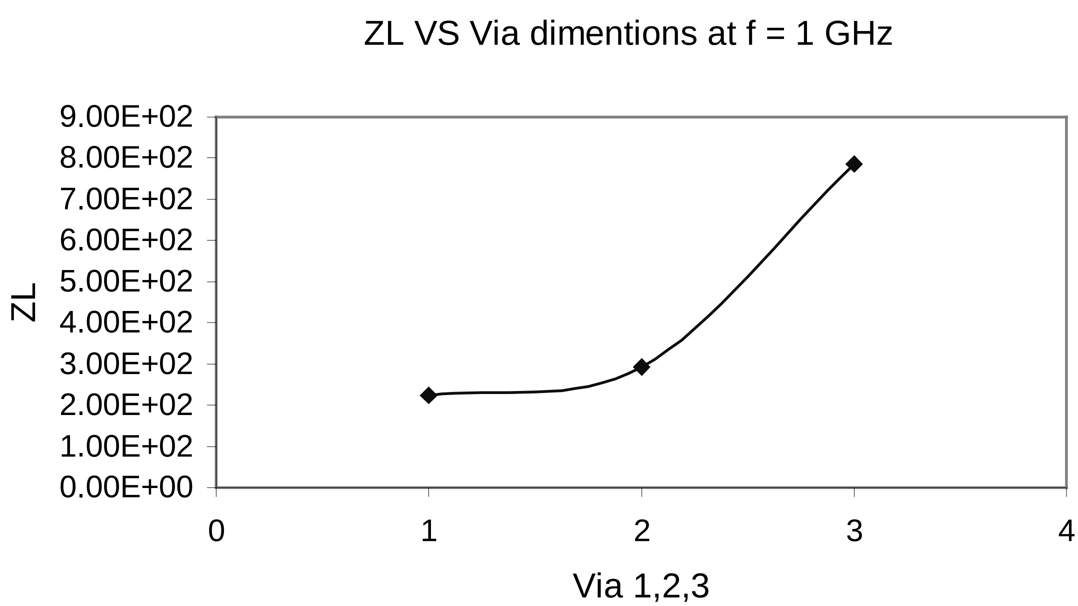


Fig 6.3 The effect of the via dimensions on the value of Zl at f=1 GHz

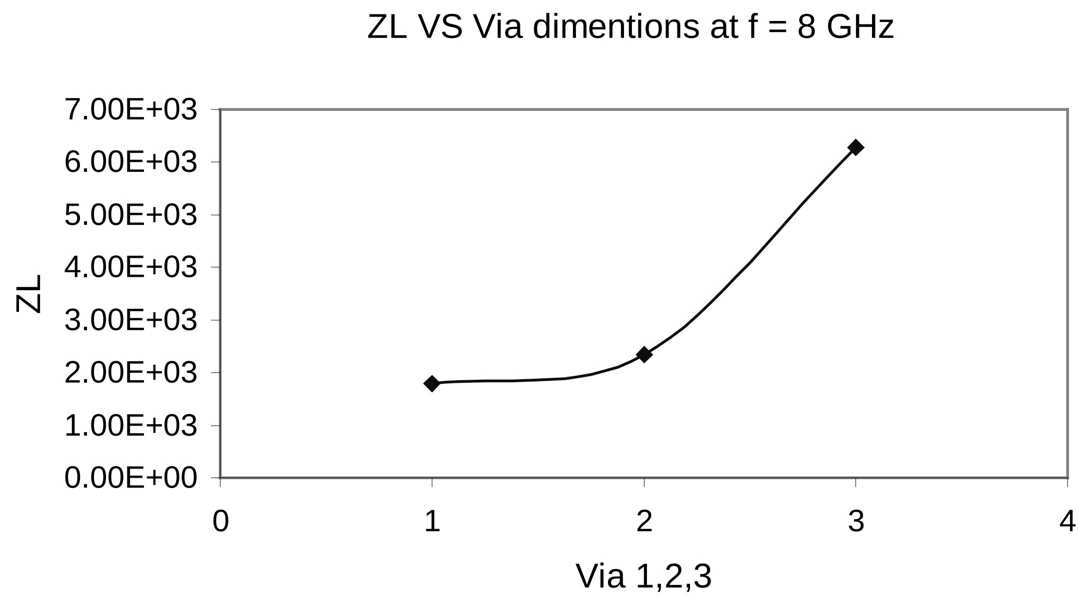


Fig 6.4 The effect of the via dimensions on the value of Zl at f= 8GHz

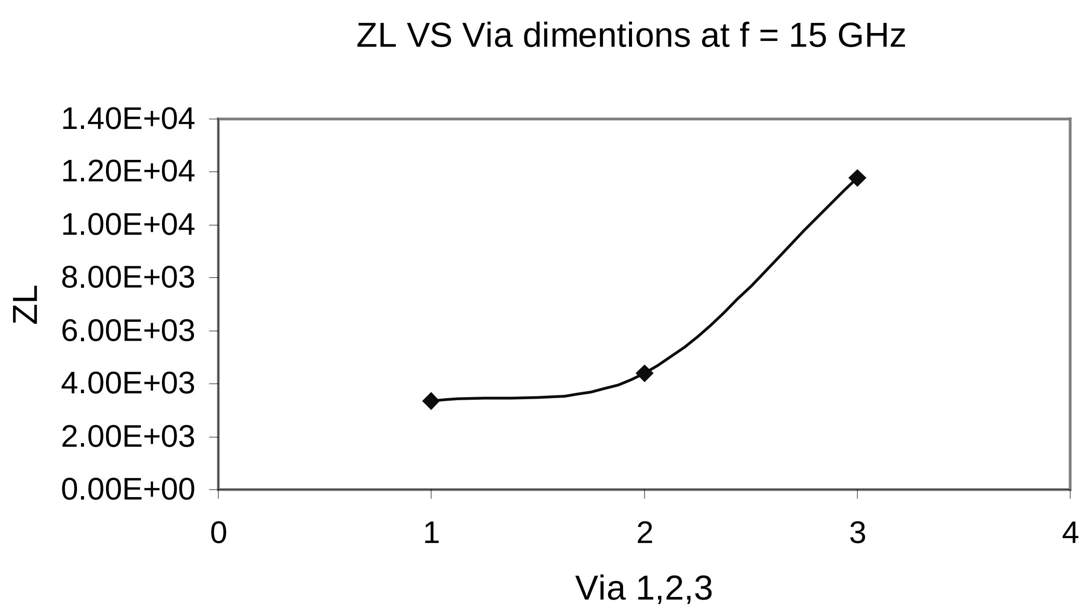


Fig 6.5 The effect of the via dimensions on the value of Zl at f=15 GHz

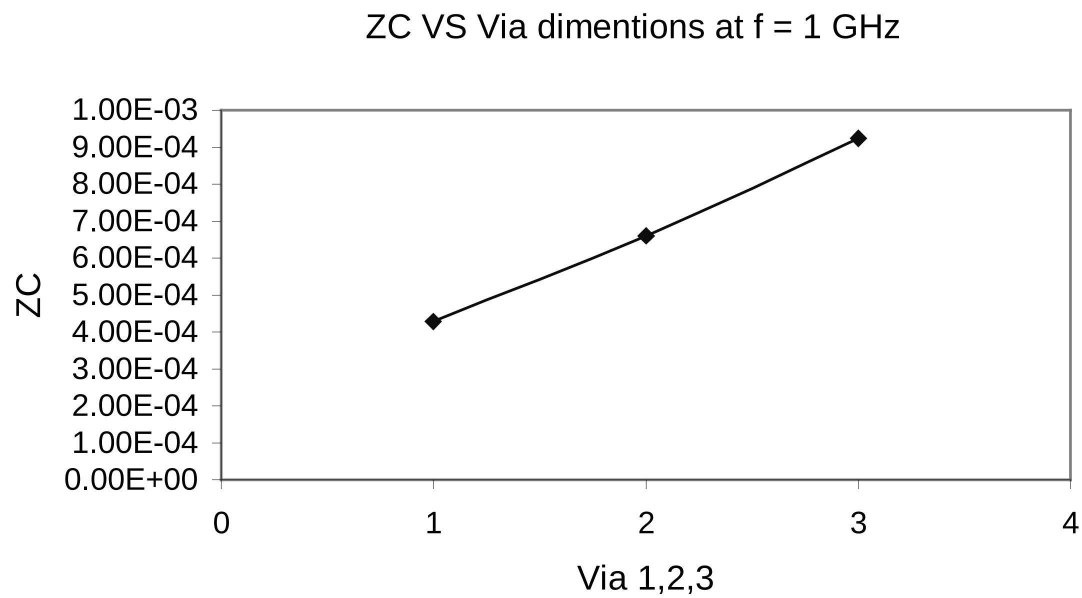


Fig 6.6 The effect of the via dimensions on the value of ZC at f=1 GHz

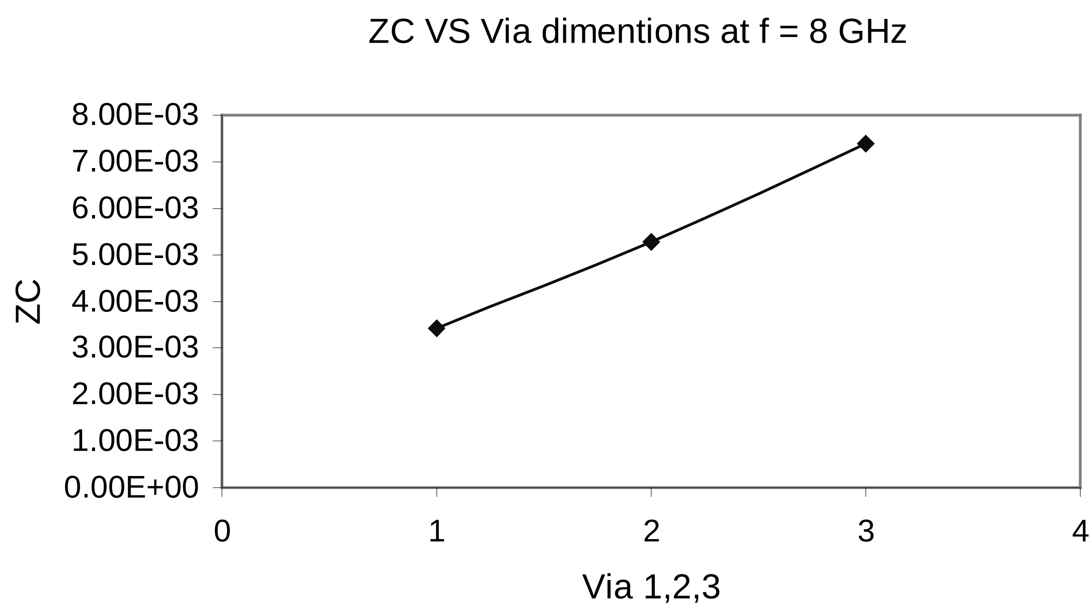


Fig 6.7 The effect of the via dimensions on the value of ZC at f=8 GHz

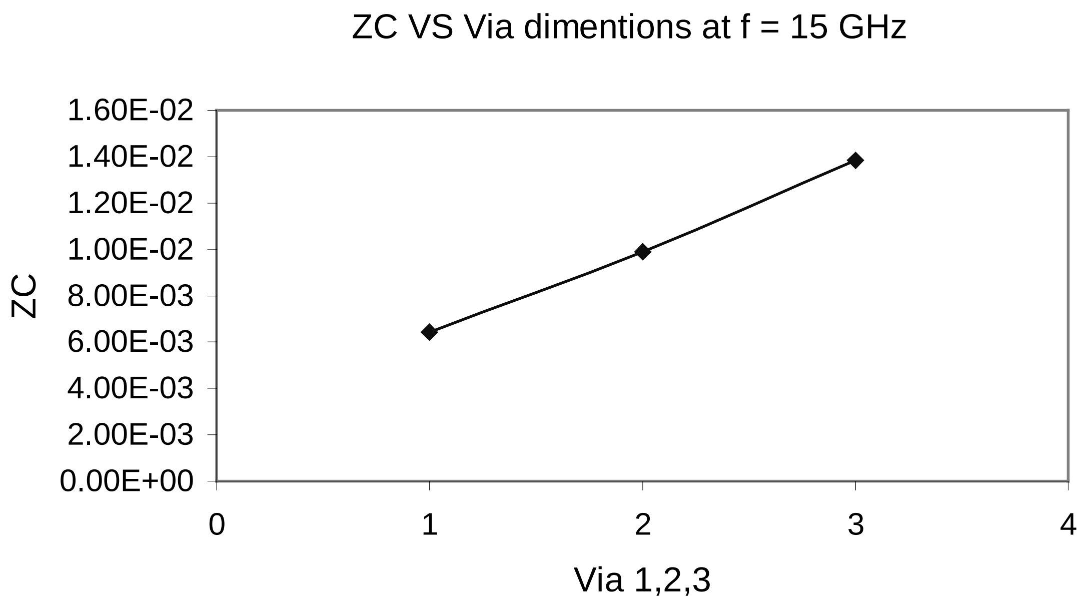


Fig 6.8 The effect of the via dimensions on the value of ZC at f=15 GHz

As we can see from these figures that the via dimensions is affecting the values of both ZL and ZC of the transitio region. These values are increasing with the increase of via dimensions with the increase of the frequency. Also from the calculations of the reactance of the transition region we noticed that, there is an increase in the reactance values with the increase of the via dimensions with the increase of the frequency, which means increase in the Q values of our resonance frequencies at the high frequency range.

As a conclusion, we can say that, the improvement in the coplaner coupled stripline resonator performance in the high frequency range after adding the via between the stripline and the coplaner line, is due to the improvement in the quality factor Q of the resonance frequencies at this frequency range. When we use a via with suitable dimensions in our design of the coplaner coupled stripline resonator, we will be able to increase the Q values of the resonance frequencies by increasing the reactance of the transition region in the high frequency range.

6.3 The Effect of the Via on the Resonance Frequency

As we had noticed in the previous section that, there is an noticed improvement in the quality factor Q of the resonance frequencies in our desired range. In this range, we had more resonance frequencies with high Q values, which means improvement in the dielectric material characterization.

In this section, we will discuss the problem we noticed while using this via between the coplaner line and the stripline in the design of the coplaner coupled stripline technique. While comparing between the S_{21} of the original design and the S_{21} of the new design with the via, we noticed that there is a slight shift in the resonance frequencies between both of them.

To be able to see how far this shift will affect on the accuracy of the dielectric material characterization; spiacially the relative permetivitty calculations; we will present a complete addresses and analysis to this phenomenon. This can be done firest, by discussing the reasons of this resonance frequencies shift and how we can minimize it. Second, by calculating how far is this shift from the original ones and what is the relation between this shift and the via and the copper plate dimensions. Third, by comparing the relative permitivitty results in both cases. Finally by finding out what is the possible solution to this problem.

As we had mentioned before, when we added a via with plate to our coplaner coupled stripline resonator design, we had a change in the position of the resonance frequencies. This change is due to the change in the reactance value of the transition region due to the existence of this via between the stripline and the coplaner line instead of the gap between them as in the original design. This change in the reactance value affecting the position of the resonance frequencies. To realize the effect of adding a reactance value to the design, one can see the effect of addling only a capacitor to a transmission line in figures (6.9), (6.10).

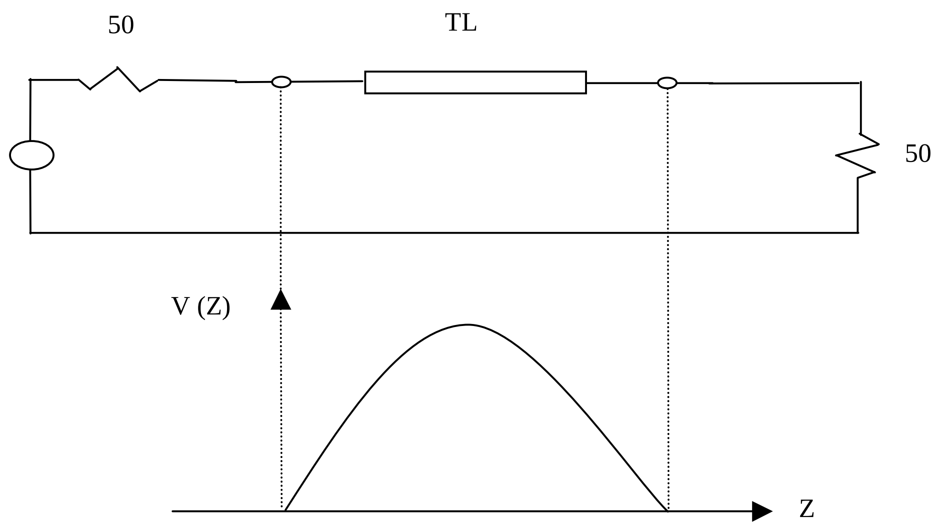


Fig 6.9 The sin wave voltage for regular the transnsimision line

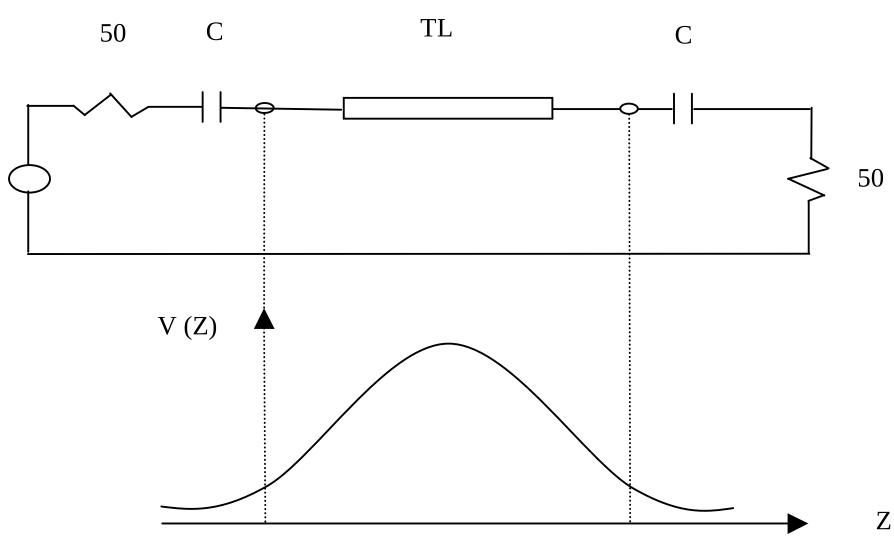


Fig 6.10 The effect of adding a capacitance on the sin wave voltage

As we can see from these Figures, for example adding capacitance to the both ends of the transmission line will affect the shape of the sine wave voltage. By the same analogy, Adding a capacitance and inductance due to the existence of the via and the copper plate in the new design of the coplaner coupled stripline resonator will affect its resonance frequencies. We can control the resultant capacitance and inductance values by controlling the via and the copper plate dimensions. So we can control the total reactance value of the transition region of the coplaner coupled stripline resonator by choosing the suitable via and copper plate dimensions. We can choose these suitable dimensions depending on the desired frequency range, which we are dealing with.

To be able to see how far this shift will affect on the accuracy of the dielectric material characterization, we need to calculate how far is this shift from the original ones and what is the relation between this shift and the via and the copper plate dimensions. This can be done by simulating the overall coplaner coupled stripline resonator using different via and copper plate dimensions, then compare the resultant resonance frequencies with the ones of the original design. For better accuracy in calculating this shift in the resonance frequencies, we will compare in both designs, the resonance frequencies (f) as well as the ratio between the resonance frequencies and the order of resonance (f/n).

We used in these simulations four vias, all of them have the same dimensions. These dimensions are (20 mil x 20 mil x h), where h is the hight of the via.The height (h) varying from 1 mil to 4 mil by step 1 mil as shown in Figure (6.11).

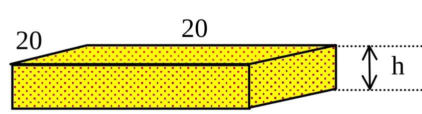


Fig 6.11 The used via dimensions in resonance shift simulations

By comparing the resonance frequencies for the coplaner cupled stripline resonator without the via and the resonance frequencies with the via at all the different via dimensions, we can see the effect of adding the via model on the position of the resonance frequencies and also on the difference between these resonance frequencies as shown in the next set of figures.

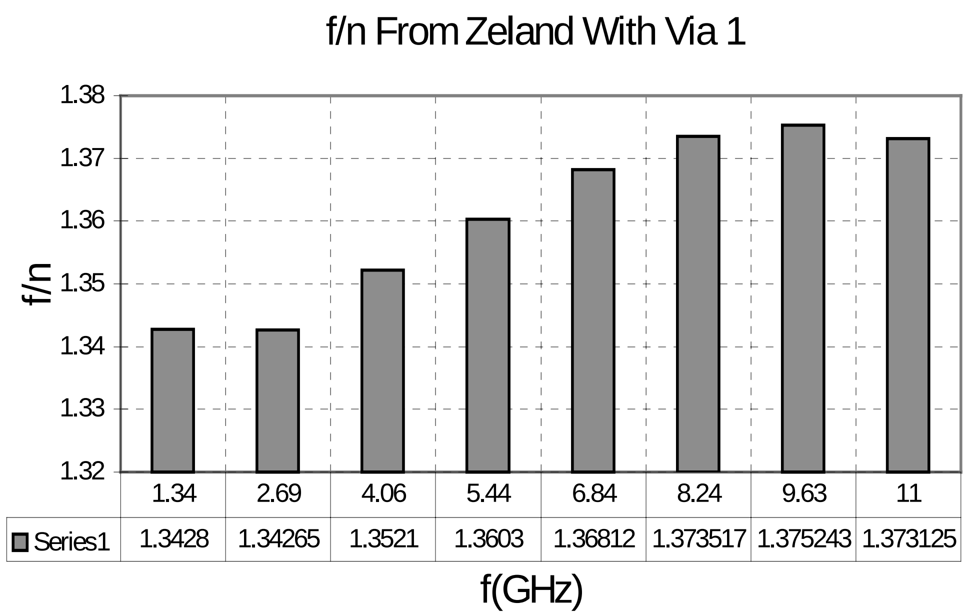


Fig 6.12 The relation between (f/n) and f from IE3D (Zeland) simulations for the CCSLR using via 1

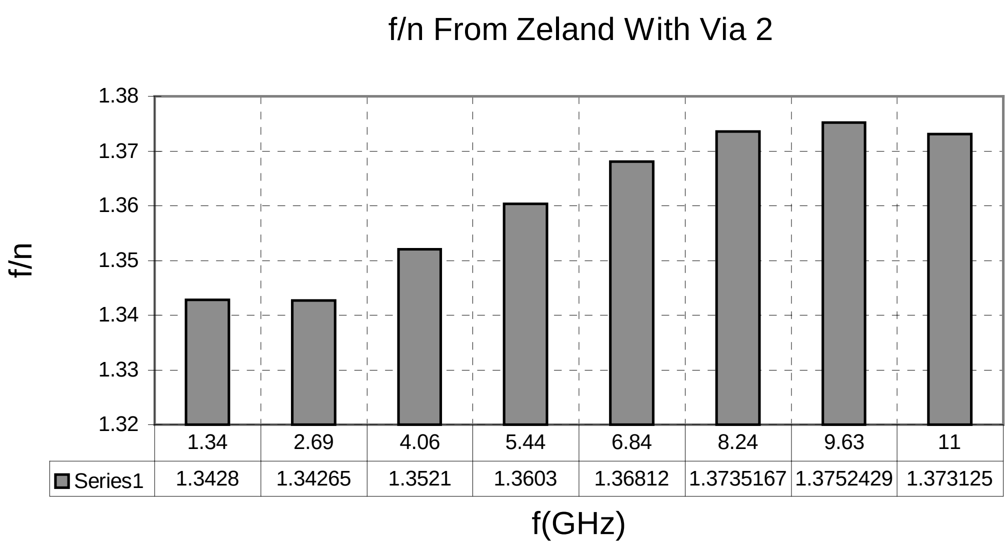
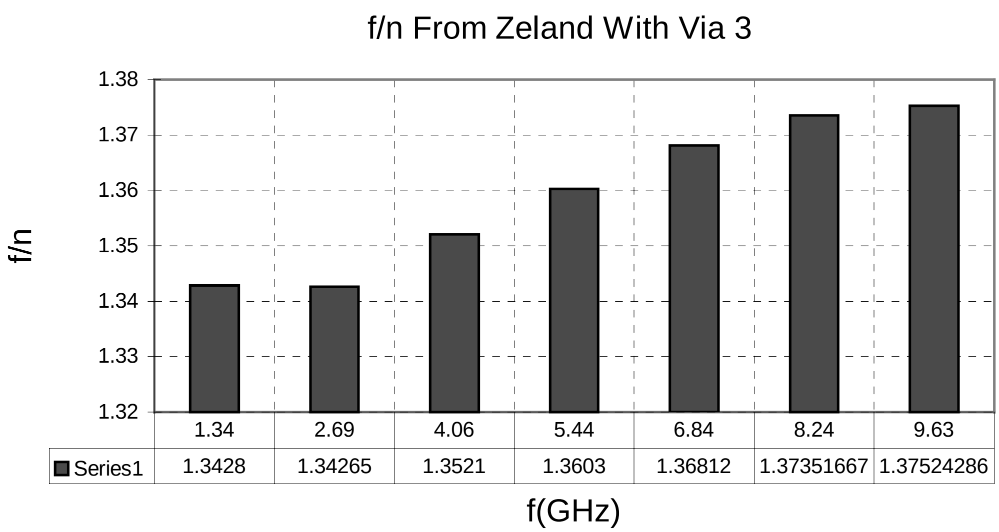


Fig 6.13 The relation between (f/n) and f from IE3D (Zeland) simulations for the CCSLR using via 2.



	1.34	2.69	4.06	5.44	6.84	8.24	9.63
Series1	1.3428	1.34265	1.3521	1.3603	1.36812	1.37351667	1.37524286

Fig 6.14 The relation between (f/n) and f from IE3D (Zeland) simulations for the CCSLR using via 3.

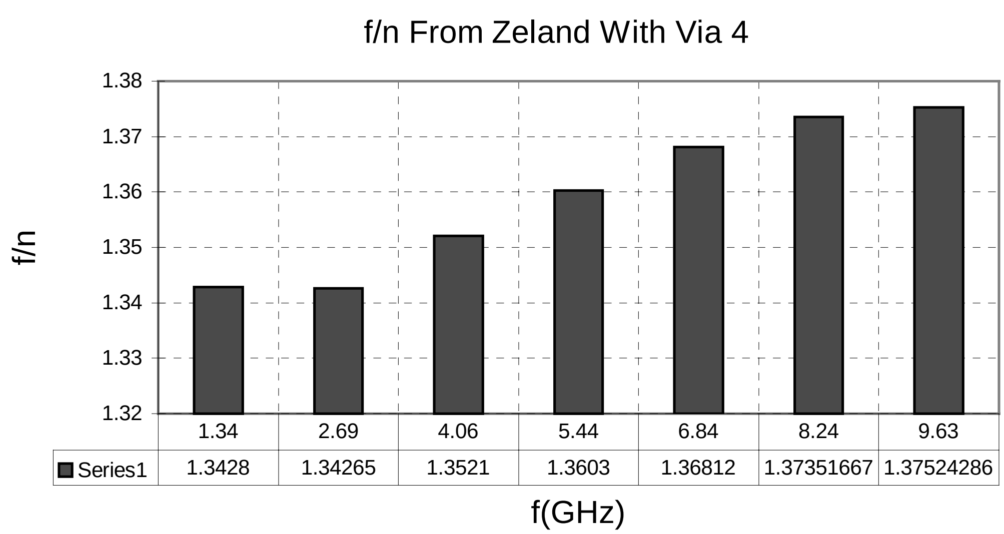


Fig 6.15 The relation between (f/n) and f from IE3D (Zeland) simulations for the CCSLR using via 4.

From the last comparison between Figures (6.12),(6.13),(6.14), and (6.15), we can see the effect of the via dimensions on the spacing between the resonance frequencies. For our design of the coplaner coupled stripline resonator dimensions and in our interesting frequency range; from 8GHz to 12GHz; we can see that, the most suitable via dimensions with minimum effect on the spacing between the resonance frequencies is via 1 with these dimensions (20 mil x 20 mil x 1 mil). As we can see in these comparisons, we only changed one dimension for the via, which is the height. The height of the via is affecting in the overall reactance of the transition region by adding a capacitance as well as inductance to the already existence reactance. This new reactance is the reason for the spacing between the resonance frequencies.

In the next two figures, we will present a comparision between the resonance frequencies for both the original design and the ones with via 1 and 3 as an example, we can see the rest of the comparisons in Appendix C.

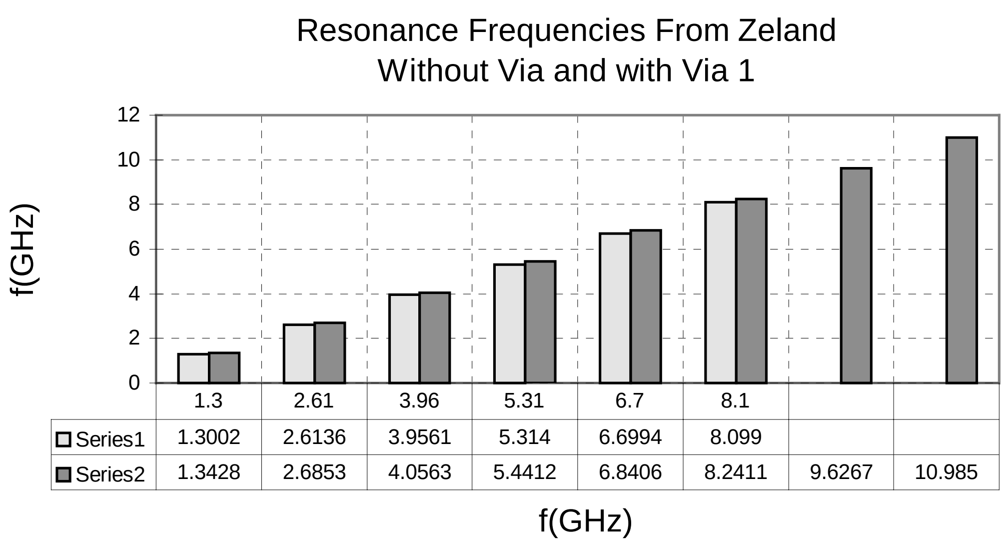
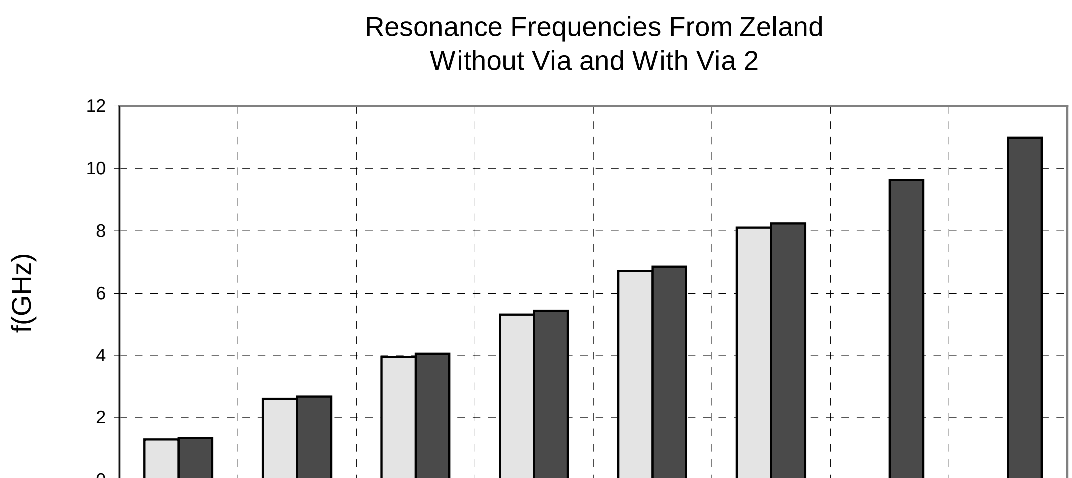


Fig 6.16 Comparison between the resonance frequencies in both the original design and the one with via 1



	1.34	2.69	4.06	5.44	6.84	8.24	9.63	11
Series2	1.3002	2.6136	3.9561	5.314	6.6994	8.099		
Series3	1.3428	2.6853	4.0563	5.4412	6.8406	8.2411	9.6267	10.985

f(GHz)

Fig 6.17 Comparison between the resonance frequencies in both the original design and the one with via 3

From these comparison we can see that the existance of the via is affectting on the position of these resonance frequencies. There is a shift between the original resonance frequencies (the ones without via) and the resonance frequencies with the via. This shift in the position of the resonance frequencies is increasing with the increase of the via hieght for the same other dimensions. Also, for our design of the coplaner coupled stripline resonator dimensions and in our interesting frequency range; from 8GHz to 12GHz; we can see that, the most suitable via dimensions with minimum effect on the shift in the resonance frequencies is still via 1.

As we had mensioned befor that our interesting frequency range is the range that we can not get any sharp resonances in the original design due to the poor Q values in this range, and this range is from 8GHz to 12GHz. In this frequency range as we can see from the last set of figuers, that these two problems of changing the positions of the resonance frequencies and the changing in the spacing between them have minimum effect in this range than the lower frequency range.

Now we can say that, by using the via in our design of the coplaner coupled stripline resonator, we had an improvement in the quality factor Q of the resonance frequencies in our interesting frequency range with minimum effect of these two problems in our interesting frequency range (8GHz to 12GHz).

We also, can see this improvement from the comparison between ε_r of the measured dielectric material along with the frequency before and after using the via in the design of the coplaner coupled stripline resonator as shown in the next set of figures and in Appendix D. The used material in all our simulations has $\varepsilon_r = 2$.

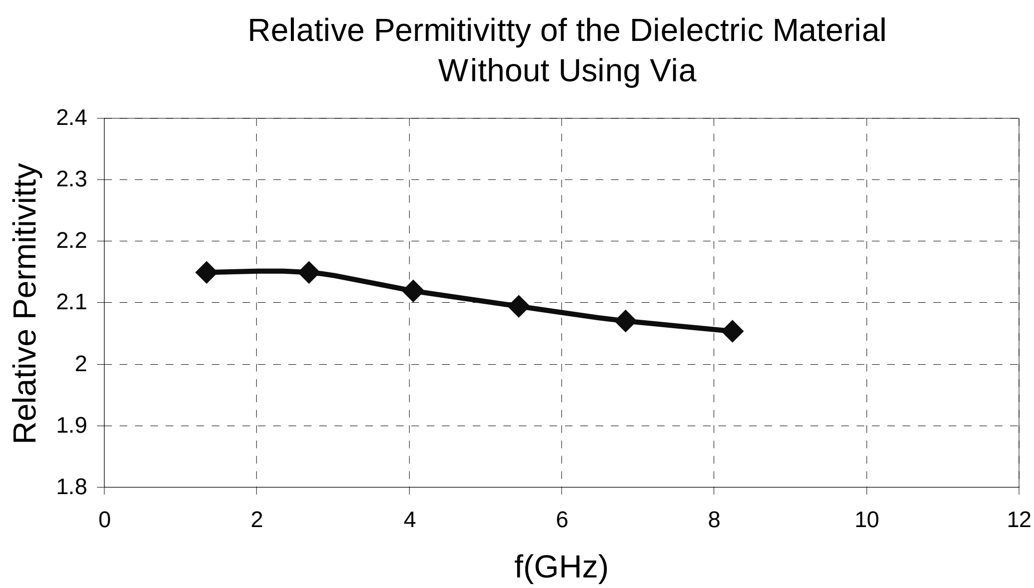


Fig 6.18 The relative permittivity of the used dielectric material without using the via

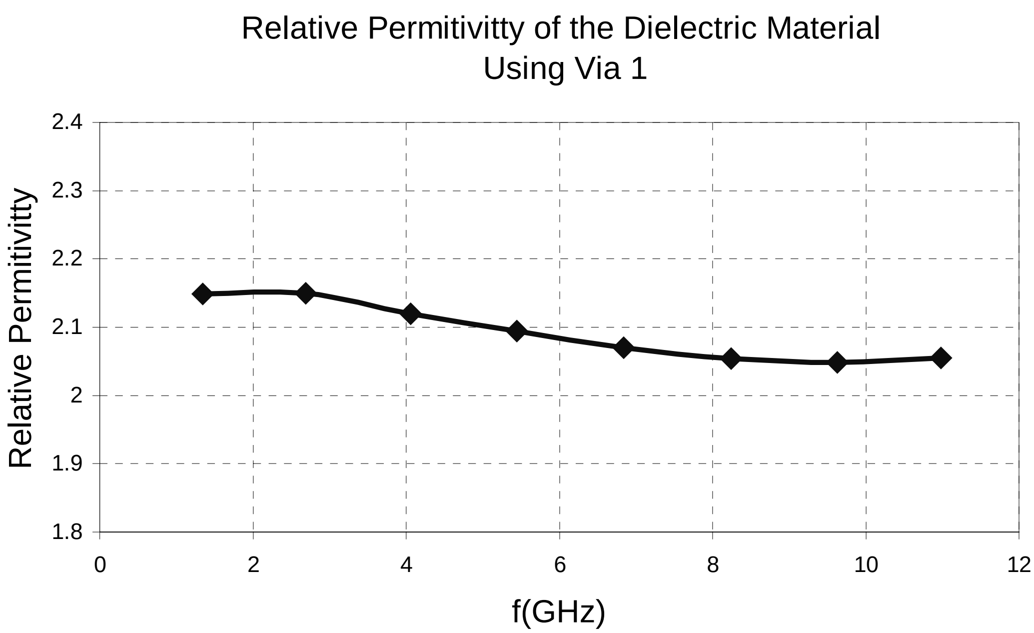


Fig 6.19 The relative permittivity of the used dielectric material using the via 1

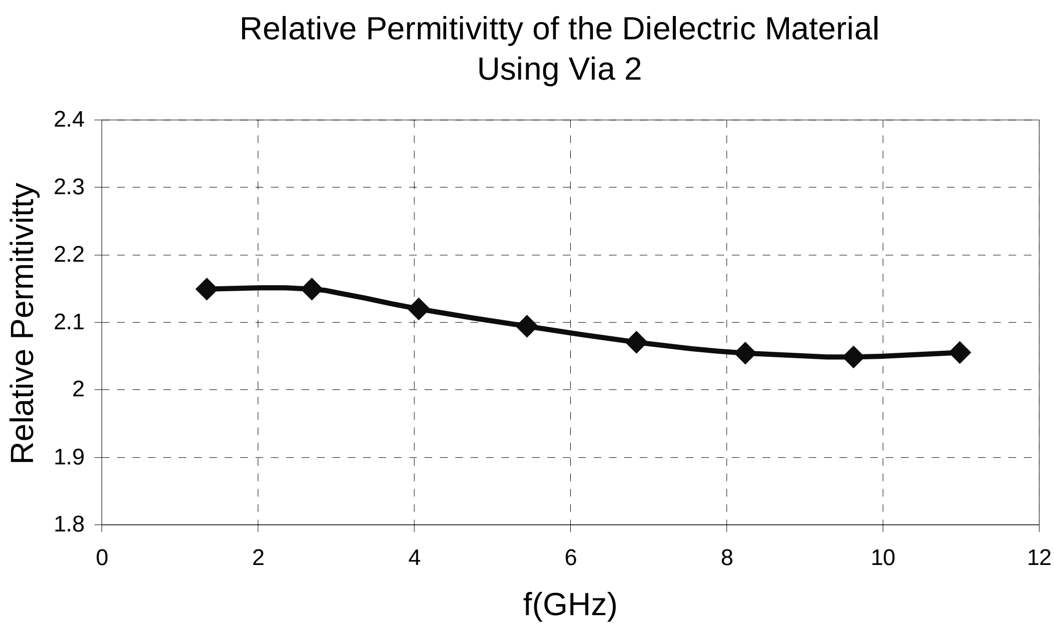


Fig 6.20 The relative permittivity of the used dielectric material

using the via 2

As we can see from these figures that, there is an improvement in the accurecy of the measuremants of the dielectric material's relative permitivitty in our interisting frequency range (8GHz to 12GHz).

We can improve the accuracy of the calculations of the dielectric constant of the material by using the suitable correction factor (ΔL) in the strip line length according to equation 6.1.

$$\sqrt{\varepsilon_r} = \frac{C}{2\left(\frac{f}{n}\right)(L + \Delta L)} \tag{6.1}$$

Where:

εr … is the relative permittivity

C … is the speed of the light in free space

f … is the resonance frequency

n … 1,2,….is the order of the resonance

L … is the stripline length

ΔL… is the correction factor

By using the suitable correction factor (ΔL) for each via dimensions and heights, we can improve our accuracy in the measurements of the relative permittivity of the dielectric materials. We can see this improvements in the relative permittivity values after using (ΔL) in our design of the coplaner coupled stripline resonator in the next set of figures and in Appendix D.

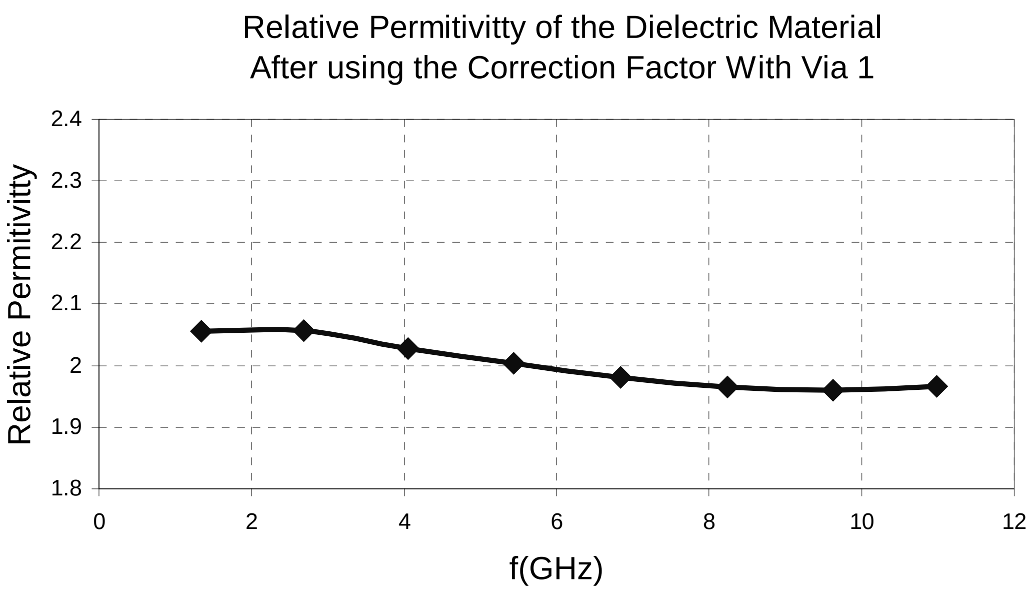


Fig 6.21 The relative permittivity of the used dielectric material after adding the correction factor with via 1

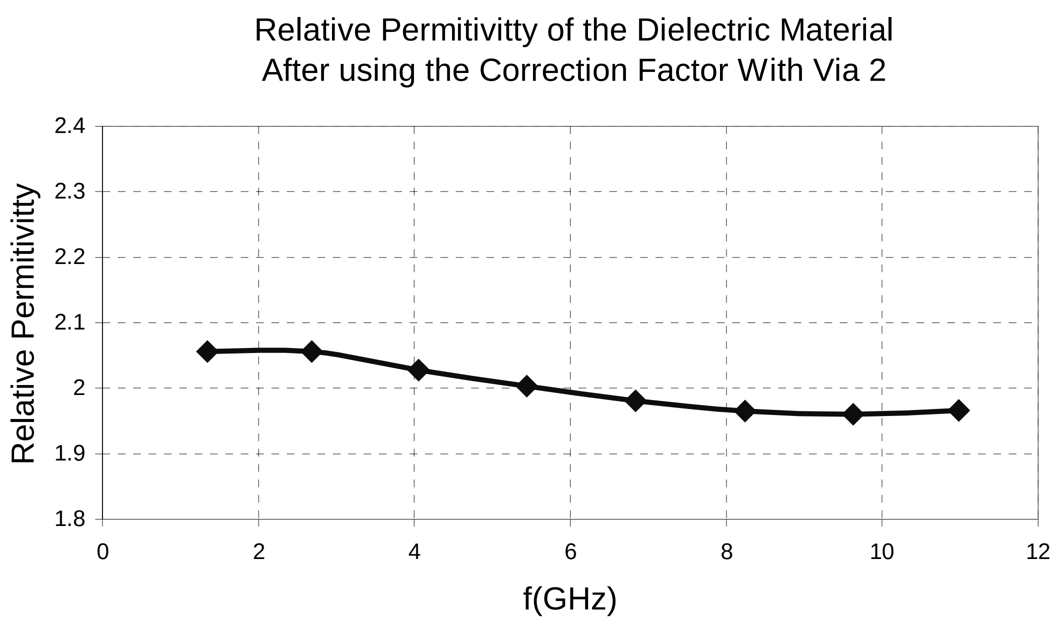


Fig 6.22 The relative permittivity of the used dielectric material

After adding the correction factor with via 2

As we can see from these sample of figures and from the rest in Apendex C, that there is an improvement in the material relative permittivity and consequently on the it's dielectric constant along the frequency range and this is after using the correction factor ΔL to the length of the stripline. We choosed the values of this correction factor ΔL according to the average in the error percentage between the calculated relative permittivity values and the given value (εr =2) at our interesting frequency range (after 8GHz) only, and not at the whole frequency range, to increase the accuracy of our results in this range. The different values of this correction factor ΔL with all the different via dimensions are given below.

Table 6.2 The correction factor value with via 1

Fr	**εr withoutΔL**	**%εr**	**εr with ΔL**	**%εr**	**ΔL**	**%ΔL**
1.3428	2.149067	7.45%	2.05593	2.04%	33.60	1.12%
2.6853	2.149547	7.48%	2.056389	2.82%		
4.0563	2.119605	5.98%	2.027745	1.39%		
5.4412	2.094128	4.71%	2.003372	0.17%		
6.8406	2.070257	3.51%	1.980535	-0.97%		
8.2411	2.05402	2.70%	1.965002	-1.75%		
9.6267	2.048867	2.44%	1.960072	-2.00%		
10.985	2.055192	2.76%	1.966123	-1.69%		
	Average	4.63%	Average	0.00%		

Table 6.3 The correction factor value with via 2

Fr	εr withoutΔL	%εr	εr with ΔL	%εr	ΔL	%ΔL
1.3428	2.149067	7.45%	2.05593	2.04%	33.6	1.12%
2.6853	2.149547	7.48%	2.056389	2.82%		
4.0563	2.119605	5.98%	2.027745	1.39%		
5.4412	2.094128	4.71%	2.003372	0.17%		
6.8406	2.070257	3.51%	1.980535	-0.97%		
8.2411	2.05402	2.70%	1.965002	-1.75%		
9.6267	2.048867	2.44%	1.960072	-2.00%		
10.985	2.055192	2.76%	1.966123	-1.69%		
	Average	4.63%	Average	0.00%		

Table 6.4 The correction factor value with via 3

Fr	εr withoutΔL	%εr	εr with ΔL	%εr	ΔL	%ΔL
1.3428	2.149067	7.45%	2.050044	2.04%	35.8	1.19%
2.6853	2.149547	7.48%	2.050502	2.53%		
4.0563	2.119605	5.98%	2.021939	1.10%		
5.4412	2.094128	4.71%	1.997636	-0.12%		
6.8406	2.070257	3.51%	1.974865	-1.26%		
8.2411	2.05402	2.70%	1.959377	-2.03%		
9.6267	2.048867	2.44%	1.954461	-2.28%		
	Average	4.90%	Average	0.00%		

Table 6.5 The correction factor value with via 4

Fr	εr withoutΔL	%εr	εr with ΔL	%εr	ΔL	%ΔL
1.3428	2.149067	7.45%	2.050044	2.04%	35.8	1.19%
2.6853	2.149547	7.48%	2.050502	2.53%		
4.0563	2.119605	5.98%	2.021939	1.10%		
5.4412	2.094128	4.71%	1.997636	-0.12%		
6.8406	2.070257	3.51%	1.974865	-1.26%		
8.2411	2.05402	2.70%	1.959377	-2.03%		
9.6267	2.048867	2.44%	1.954461	-2.28%		
	Average	4.90%	Average	0.00%		

As depicted from these tables, only correction factors with values from 33.6 mil to 35.8 mil according to the used via dimensions, have to be added to the original length of the center stripline of length 2540 mil, to get this improvement in the relative permitivitty calculations. As we had mensioned befor, that we choosed the values of this correction factor ΔL according to the avarage in the error percentage between the calculated relative permittivity values and the given value (εr =2) at our interesting frequency range (after 8GHz) only, and not at the whole frequency range, to increase the accurecy of our resuts in this range.

As a conclusion we can say that, using the via in the design of the coplaner coupled stripline resonator is affectting on the position of its resonance frequencies. There is a slight shift between the original resonance frequencies and the ones of the design with the via. This shift is increasing with the increase of the via hieght for the same other dimensions. The most suitable via dimensions with minimum effect on the shift in the resonance frequencies, for our design of the coplaner coupled stripline resonator dimensions and in our interesting frequency range, is via 1 with these dimensions (20 mil x 20 mil x 1 mil).

According to this chapter's results, the improvement in the overll response of the coplaner coupled stripline resonator is depicted from the accurecy of the calculations of the dielectric material's relative permitivitty in our interisting frequency range (8GHz to 12GHz). We can increase this accurecy by adding a correction factor ΔL to the length of the center stripline in our coplaner coupled stripline resonator. Only correction factors with values from 33.6 mil to 35.8 mil according to the used via dimensions, have to be added to the original length of the center stripline of length 2540 mil, to get an acceptable improvement in the relative permitivitty values.

Finally, we can say that, by using the via in our design of the coplaner coupled stripline resonator, we had an improvement in the quality factor Q of the resonance frequencies in our interesting frequency range with minimum effect of the resonance frequencies shift problem. In addition, adding the suitable correction factor ΔL to the length of the center stripline in the coplaner coupled stripline resonator, according to the used via dimensions, will help in improving the overall frequency response.

Chapter 7

Summary and Conclusions

In this dissertation we presented one of the most common used techniques in material characterization, which is the coplaner coupled stripline resonator technique. We started our dissertation by an overview and comparison between the coplaner coupled stripline resonator technique and both the stripline and the stripline resonator techniques. We presented the equations and theory necessary to relate the response of the coplaner coupled stripline resonator to the characteristics of the materials from which it is constructed.

During this work we discussed two important issues related to the design of coplaner coupled stripline resonator. The first issue was the proper design of the coupling gap dimensions. It is necessary to obtain the proper gap size to provide acceptable coupling of the resonator to compromise between very strong coupling where radiation loss becomes significant and very week coupling which lead to difficulty in detecting resonance. For this reason, and in order to have a complete appreciation of the effect of the gap dimensions on the response of the coplaner coupled stripline resonator, we simulated the transition region for a set of coplaner coupled stripline resonators with different gap dimensions.

From these simulations, we noticed that the capacitor behavior of the gap turns into more complex one above some certain frequency depending on the dimensions of the gap. We verified that observation by deriving the lumped element model of the gap using Pspice software. The lumped element model of the coupling region took the approximate form of a series L – C combination. At the lower frequencies the C part of this model dominates and hence the capacitive behavior of the gap. However, at the upper frequencies, the L dominates over the C resulting in an inductive coupling. The impedance of the L – C combination is high at both ends of the frequency range resulting in desired weak coupling to and from the stripline resonator to minimize the loading effect of the source and load side impedances. The L- C combination, and hence the coupling region exhibit a low impedance around a certain frequency at which $\omega \mathbf{L} = \frac{\mathbf{1}}{\omega \mathbf{C}}$. At this frequency and in its vicinity, the coupling reaches its peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value. In this frequency range, measurement of the dielectric properties looses its accuracy because the lowered Q values means inaccuracies in determining the resonant frequencies as well as great error in determining the Q_c and Q_d terms. In an attempt to remedy this increase coupling behavior, reactive tuning elements are sought to be added to the transition region. We found that we can improve the behavior of the gap and the overall resonator response at higher frequencies by adding a compensating shunt resonant branch.

Also from the comparison between the S_{21} of the transition region with the lumped element model of the gab using Pspice software and the S_{21} of the original transmission region with the original gab using IE3D simulation software, we had a good agreement in S_{21} indicating good modeling accuracy. From the S_{21} vs frequency results of these simulations, we had these conclusions:

- A transition region with a large gap would cause the coupling to be very week to observe resonance.
- A transition region with a narrow gap would increase external loading effects that degrade the quality factor of resonance, also decrease the frequency range of operation of the resonator.
- The capacitive behavior of the gap turns into more complex one above some certain frequency depending on the dimensions of the gap
- A relatively small overlap would help improve the behavior of the gap at higher frequencies.
- We can improve the behavior of the gap and the overall resonator response at higher frequencies by adding a compensating shunt resonant branch.

The second issue we discussed in this dissertation was the main problem we met while the practical measurements using the CCSLR technique in material characterization. The problem represents the limitation in the frequency range, which we can get good Q values (sharp resonance) during the measurements. At this frequency range, the coupling reaches its peak value for a given stripline resulting in excessive loading to the resonator and thus a lowered Q value. In this frequency range, measurements of the dielectric properties looses its accuracy because the lowered Q values means inaccuracies in determining the resonant frequencies as well as great error in determining the Q_c and Q_d terms. For this reason we presented in this dissertation two approaches in optimizing the design of CCSLR to be able to extend the frequency range of the accurate measurements.

In the first approach we tried all the possible combinations between all the possible dimensions of the three sections of the CCSLR (Coplaner, Transition region, and the center stripline). Using the IE3D simulation software we simulated all these designs, and from the results of these simulations we presented the most optimum design from this set with its optimum dimensions.

In the second approach we used the lumped element model of the gap from the simulation of the transition region as a guide in optimizing the design of the CCSLR. We tried to compensate the capacitance and the inductance behavior of the gab at low and high frequencies, which affects the Q values and consequently the resonance frequencies, by using a via between the coplaner line and the center stripline. The via can be represented as an inductance, but if we used a copper plate with different separation distance between the plate and the via, it can be represented as a combination of inductance and capacitance. The values of these inductance and capacitance depends on dimensions and shapes of both the via and the copper plate and also the separation distance between them. Simulations of different designs of the CCSLR using different via and copper plates dimensions as well as different separation distances between them were made. From the comparisons between the S_{21} of these new designs and the original one, we had an improvement in the overall response of the CCSLR. This improvement can be recognized from the extension of the frequency range, which has good Q values (sharp resonance). This means improvement in the accuracy of the dielectric properties measurement.

A complete analysis and explanation for the reasons of the improvement in the quality factor (Q) at the high frequency range after using the via were presented. This has been done by simulating the lumped elements model of the used via using IE3D simulation software. By using this model and by the impedance calculations for this model verses frequency, we were able to recognize the capacitance and the inductance behavior of this via along our frequency range, which gave us a complete explanation of this phenomena.

Finally, we discussed the issue of the shift in the resonance frequencies due to the existence of the via in the new design. We used the same lumped elements model of the via to simulate the whole CCSLR using Pspice simulation software, and compared the resultant resonance frequency with the original one from Zeland simulation software to see how fare is this shift in the resonance frequency. Also using different via dimensions we discussed the effect of these via dimensions on this shift. We explained how to increase the accuracy of the dielectric constant measurements by using the correction factor (Δ L) in the stripline length (L) in the new design of the CCSLR.

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Appendix A

MatLab Programs For Calculating the S Parameters for the CCSLR from the S parameters of the individual modules

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program is used to find the S parameters of the coplaner       %
% coupled stripline resonator given the S parameters of the individual%
% modules, these are the coplaner line 1, the transition 1 and the    %
% strip line 1                                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% Reading the coplaner line S parameters
%----------------------------------------


clear
n=20;

load copl1.txt

Freq=copl1(:,1);
S11a=copl1(:,2).*(cos(copl1(:,3)*pi/180)+i*sin(copl1(:,3).*pi/180));
S12a=copl1(:,4).*(cos(copl1(:,5)*pi/180)+i*sin(copl1(:,5).*pi/180));
S21a=S12a;
S22a=S11a;

Freq=interp(Freq,n);
S11a=interp(S11a,n);   S12a=interp(S12a,n);
S21a=interp(S21a,n);   S22a=interp(S22a,n);
% T parameters;

T11a=1./S21a ;     T12a=-S22a./S21a;

T21a=S11a./S21a;   T22a=S12a-S11a.*S22a./S21a;


%Reading the transition S parameters
%--------------------------------


load trans1.txt;

Freq=trans1(:,1);

S11b=trans1(:,2).*(cos(trans1(:,3)*pi/180)+i*sin(trans1(:,3).*pi/180));
S21b=trans1(:,4).*(cos(trans1(:,5)*pi/180)+i*sin(trans1(:,5).*pi/180));
S12b=trans1(:,6).*(cos(trans1(:,7)*pi/180)+i*sin(trans1(:,7).*pi/180));
S22b=trans1(:,8).*(cos(trans1(:,9)*pi/180)+i*sin(trans1(:,9).*pi/180));

S11b=interp(S11b,n);   S12b=interp(S12b,n);
S21b=interp(S21b,n);   S22b=interp(S22b,n);

T11b=1./S21b ;     T12b=-S22b./S21b;

T21b=S11b./S21b;   T22b=S12b-S11b.*S22b./S21b;
```

```
% Reading the stripline S parameters
%---------------------------------------


load stl1.txt


ext=2540/54;
Z=35.84;
load stl1.txt

Freq=stl1(:,1);
S11c=stl1(:,2).*(cos(stl1(:,3)*pi/180)+i*sin(stl1(:,3).*pi/180));
S12c=stl1(:,4).*(cos(stl1(:,5)*pi/180)+i*sin(stl1(:,5).*pi/180));
S21c=S12c;
S22c=S11c;

Freq=interp(Freq,n);
S11c=interp(S11c,n);
S21c=interp(S21c,n);
S22c=S11c;
S12c=S21c;

prc=S21c.^ext;

rho=(50-Z)/(50+Z);

S21c=(1-rho^2).*prc./(1-rho^2.*prc.^2);

S11c=-rho.*(1-prc.^2)./(1-rho^2*prc.^2);

S22c=S11c;
S12c=S21c;
T11c=1./S21c ;     T12c=-S22c./S21c;

T21c=S11c./S21c;   T22c=S12c-S11c.*S22c./S21c;


% Reversed transition
%-------------------


S11d=S22b;   S12d=S21b;
S21d=S12b;   S22d=S11b;

T11d=1./S21d ;     T12d=-S22d./S21d;

T21d=S11d./S21d;   T22d=S12d-S11d.*S22d./S21d;


for k=1:length(Freq)

Ta(1,1)=T11a(k); Ta(1,2)=T12a(k);
Ta(2,1)=T21a(k); Ta(2,2)=T22a(k);

Tb(1,1)=T11b(k); Tb(1,2)=T12b(k);
Tb(2,1)=T21b(k); Tb(2,2)=T22b(k);
```

```
Tc(1,1)=T11c(k); Tc(1,2)=T12c(k);
Tc(2,1)=T21c(k); Tc(2,2)=T22c(k);

Td(1,1)=T11d(k); Td(1,2)=T12d(k);
Td(2,1)=T21d(k); Td(2,2)=T22d(k);

T=Ta*Tb*Tc*Td*Ta;
S11(k)=T(2,1)/T(1,1);   S12(k)=T(2,2)-T(2,1)*T(1,2)/T(1,1);
S21(k)=1/T(1,1);        S22(k)=-T(1,2)/T(1,1);

end;

plot(Freq,20*log10(abs(S21)));


title('S21 vs f in GHZ');
xlabel('Frequency GHZ');
ylabel('S21');

grid;


x=20*log10(abs(S21b));
y=20*log10(abs(S21));
fid=fopen('res111.txt','w');

for k=1:length(Freq)

fprintf(fid,'\n  %e %e %e ',Freq(k),x(k),y(k));

end;

fclose(fid);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program is used to find the S parameters of the coplaner      %
% coupled stripline resonator given the S parameters of the individual%
% modules, these are the coplaner line 1, the transition 4 and the   %
% strip line 1                                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% reading the coplaner line S parameters
%----------------------------------------


clear
n=20;

load copl1.txt

Freq=copl1(:,1);
S11a=copl1(:,2).*(cos(copl1(:,3)*pi/180)+i*sin(copl1(:,3).*pi/180));
S12a=copl1(:,4).*(cos(copl1(:,5)*pi/180)+i*sin(copl1(:,5).*pi/180));
S21a=S12a;
S22a=S11a;

Freq=interp(Freq,n);
S11a=interp(S11a,n);   S12a=interp(S12a,n);
S21a=interp(S21a,n);   S22a=interp(S22a,n);
% T parameters;

T11a=1./S21a ;     T12a=-S22a./S21a;

T21a=S11a./S21a;   T22a=S12a-S11a.*S22a./S21a;

%Reading the transition S parameters
%---------------------------------

load trans4.txt;

Freq=trans4(:,1);

S11b=trans4(:,2).*(cos(trans4(:,3)*pi/180)+i*sin(trans4(:,3).*pi/180));
S21b=trans4(:,4).*(cos(trans4(:,5)*pi/180)+i*sin(trans4(:,5).*pi/180));
S12b=trans4(:,6).*(cos(trans4(:,7)*pi/180)+i*sin(trans4(:,7).*pi/180));
S22b=trans4(:,8).*(cos(trans4(:,9)*pi/180)+i*sin(trans4(:,9).*pi/180));

S11b=interp(S11b,n);   S12b=interp(S12b,n);
S21b=interp(S21b,n);   S22b=interp(S22b,n);

T11b=1./S21b ;     T12b=-S22b./S21b;

T21b=S11b./S21b;   T22b=S12b-S11b.*S22b./S21b;
```

```
% Reading the stripline S parameters
%---------------------------------------


load stl1.txt


ext=2540/54;
Z=35.84;
load stl1.txt

Freq=stl1(:,1);
S11c=stl1(:,2).*(cos(stl1(:,3)*pi/180)+i*sin(stl1(:,3).*pi/180));
S12c=stl1(:,4).*(cos(stl1(:,5)*pi/180)+i*sin(stl1(:,5).*pi/180));
S21c=S12c;
S22c=S11c;

Freq=interp(Freq,n);
S11c=interp(S11c,n);
S21c=interp(S21c,n);
S22c=S11c;
S12c=S21c;

prc=S21c.^ext;

rho=(50-Z)/(50+Z);

S21c=(1-rho^2).*prc./(1-rho^2.*prc.^2);

S11c=-rho.*(1-prc.^2)./(1-rho^2*prc.^2);

S22c=S11c;
S12c=S21c;
T11c=1./S21c ;     T12c=-S22c./S21c;

T21c=S11c./S21c;   T22c=S12c-S11c.*S22c./S21c;



% reversed transition
%-------------------



S11d=S22b;   S12d=S21b;
S21d=S12b;   S22d=S11b;

T11d=1./S21d ;     T12d=-S22d./S21d;

T21d=S11d./S21d;   T22d=S12d-S11d.*S22d./S21d;


for k=1:length(Freq)
```

```
Ta(1,1)=T11a(k); Ta(1,2)=T12a(k);
Ta(2,1)=T21a(k); Ta(2,2)=T22a(k);

Tb(1,1)=T11b(k); Tb(1,2)=T12b(k);
Tb(2,1)=T21b(k); Tb(2,2)=T22b(k);

Tc(1,1)=T11c(k); Tc(1,2)=T12c(k);
Tc(2,1)=T21c(k); Tc(2,2)=T22c(k);

Td(1,1)=T11d(k); Td(1,2)=T12d(k);
Td(2,1)=T21d(k); Td(2,2)=T22d(k);

T=Ta*Tb*Tc*Td*Ta;
S11(k)=T(2,1)/T(1,1);   S12(k)=T(2,2)-T(2,1)*T(1,2)/T(1,1);
S21(k)=1/T(1,1);        S22(k)=-T(1,2)/T(1,1);

end;

plot(Freq,20*log10(abs(S21)));
x=20*log10(abs(S21b));
y=20*log10(abs(S21));
fid=fopen('res141.txt','w');

for k=1:length(Freq)

fprintf(fid,'\n  %e %e %e ',Freq(k),x(k),y(k));

end;

fclose(fid);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program is used to find the S parameters of the coplaner      %
% coupled stripline resonator given the S parameters of the individual%
% modules, these are the coplaner line 1, the transition 1 and the    %
% strip line 4                                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% reading the coplaner line S parameters
%---------------------------------------


clear
n=20;

load copl1.txt

Freq=copl1(:,1);
S11a=copl1(:,2).*(cos(copl1(:,3)*pi/180)+i*sin(copl1(:,3).*pi/180));
S12a=copl1(:,4).*(cos(copl1(:,5)*pi/180)+i*sin(copl1(:,5).*pi/180));
S21a=S12a;
S22a=S11a;

Freq=interp(Freq,n);
S11a=interp(S11a,n);   S12a=interp(S12a,n);
S21a=interp(S21a,n);   S22a=interp(S22a,n);
% T parameters;

T11a=1./S21a ;     T12a=-S22a./S21a;

T21a=S11a./S21a;   T22a=S12a-S11a.*S22a./S21a;



%Reading the transition S parameters
%---------------------------------


load trans1.txt;

Freq=trans1(:,1);

S11b=trans1(:,2).*(cos(trans1(:,3)*pi/180)+i*sin(trans1(:,3).*pi/180));
S21b=trans1(:,4).*(cos(trans1(:,5)*pi/180)+i*sin(trans1(:,5).*pi/180));
S12b=trans1(:,6).*(cos(trans1(:,7)*pi/180)+i*sin(trans1(:,7).*pi/180));
S22b=trans1(:,8).*(cos(trans1(:,9)*pi/180)+i*sin(trans1(:,9).*pi/180));

S11b=interp(S11b,n);   S12b=interp(S12b,n);
S21b=interp(S21b,n);   S22b=interp(S22b,n);

T11b=1./S21b ;     T12b=-S22b./S21b;

T21b=S11b./S21b;   T22b=S12b-S11b.*S22b./S21b;
```

```
% Reading the stripline S parameters
%---------------------------------------


load stl4.txt


ext=2540/54;
Z=50.2;
load stl4.txt

Freq=stl4(:,1);
S11c=stl4(:,2).*(cos(stl4(:,3)*pi/180)+i*sin(stl4(:,3).*pi/180));
S12c=stl4(:,4).*(cos(stl4(:,5)*pi/180)+i*sin(stl4(:,5).*pi/180));
S21c=S12c;
S22c=S11c;

Freq=interp(Freq,n);
S11c=interp(S11c,n);
S21c=interp(S21c,n);
S22c=S11c;
S12c=S21c;

prc=S21c.^ext;

rho=(50-Z)/(50+Z);

S21c=(1-rho^2).*prc./(1-rho^2.*prc.^2);

S11c=-rho.*(1-prc.^2)./(1-rho^2*prc.^2);

S22c=S11c;
S12c=S21c;
T11c=1./S21c ;     T12c=-S22c./S21c;

T21c=S11c./S21c;   T22c=S12c-S11c.*S22c./S21c;

% reversed transition
%-------------------

S11d=S22b;   S12d=S21b;
S21d=S12b;   S22d=S11b;

T11d=1./S21d ;     T12d=-S22d./S21d;

T21d=S11d./S21d;   T22d=S12d-S11d.*S22d./S21d;


for k=1:length(Freq)

Ta(1,1)=T11a(k); Ta(1,2)=T12a(k);
Ta(2,1)=T21a(k); Ta(2,2)=T22a(k);

Tb(1,1)=T11b(k); Tb(1,2)=T12b(k);
Tb(2,1)=T21b(k); Tb(2,2)=T22b(k);
```

```
Tc(1,1)=T11c(k); Tc(1,2)=T12c(k);
Tc(2,1)=T21c(k); Tc(2,2)=T22c(k);

Td(1,1)=T11d(k); Td(1,2)=T12d(k);
Td(2,1)=T21d(k); Td(2,2)=T22d(k);

T=Ta*Tb*Tc*Td*Ta;
S11(k)=T(2,1)/T(1,1);   S12(k)=T(2,2)-T(2,1)*T(1,2)/T(1,1);
S21(k)=1/T(1,1);        S22(k)=-T(1,2)/T(1,1);

end;

plot(Freq,20*log10(abs(S21)));
x=20*log10(abs(S21b));
y=20*log10(abs(S21));
fid=fopen('res114.txt','w');

for k=1:length(Freq)

fprintf(fid,'\n  %e %e %e ',Freq(k),x(k),y(k));

end;

fclose(fid);
```

Appendix B

Comparison between the Overall S21 of the Original Design and the other Different Designs

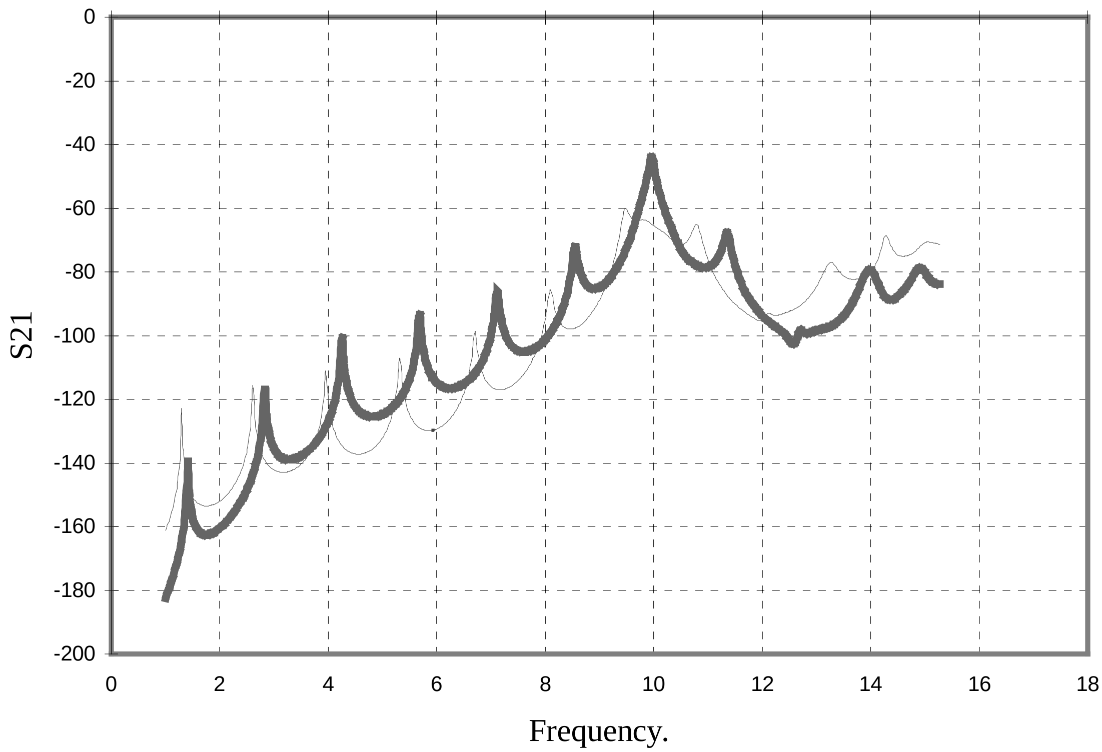


Fig B.1 Comparison between the overall S21 of the original design with different designs (132 VS 194)

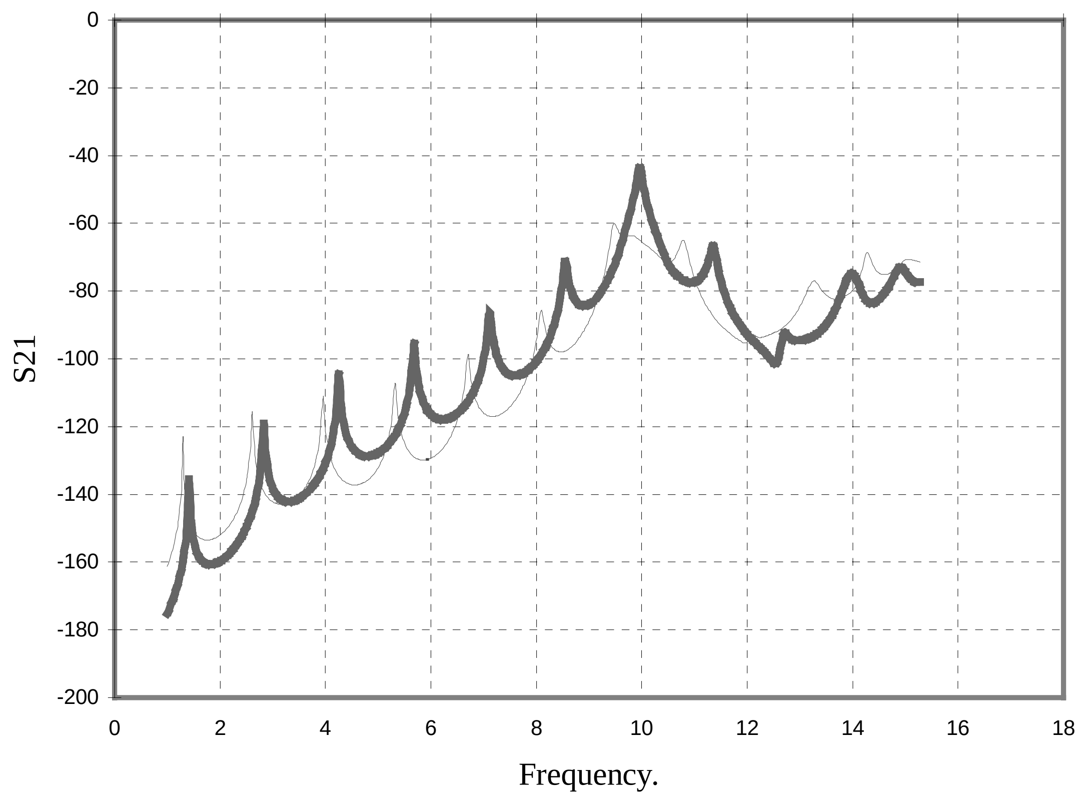


Fig B.2 Comparison between the overall S21 of the original design with different designs (132 VS 314)

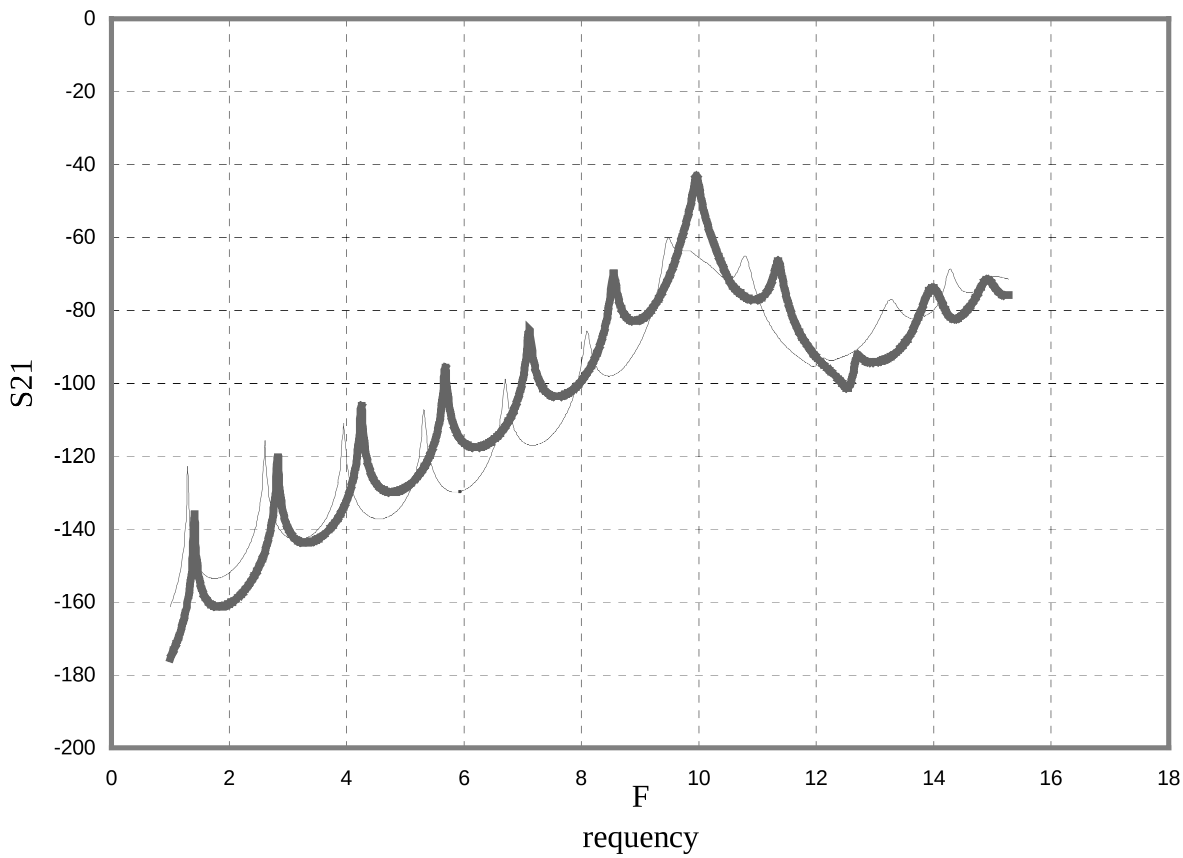


Fig B.3 Comparison between the overall S21 of the original design with different designs (132 VS 514)

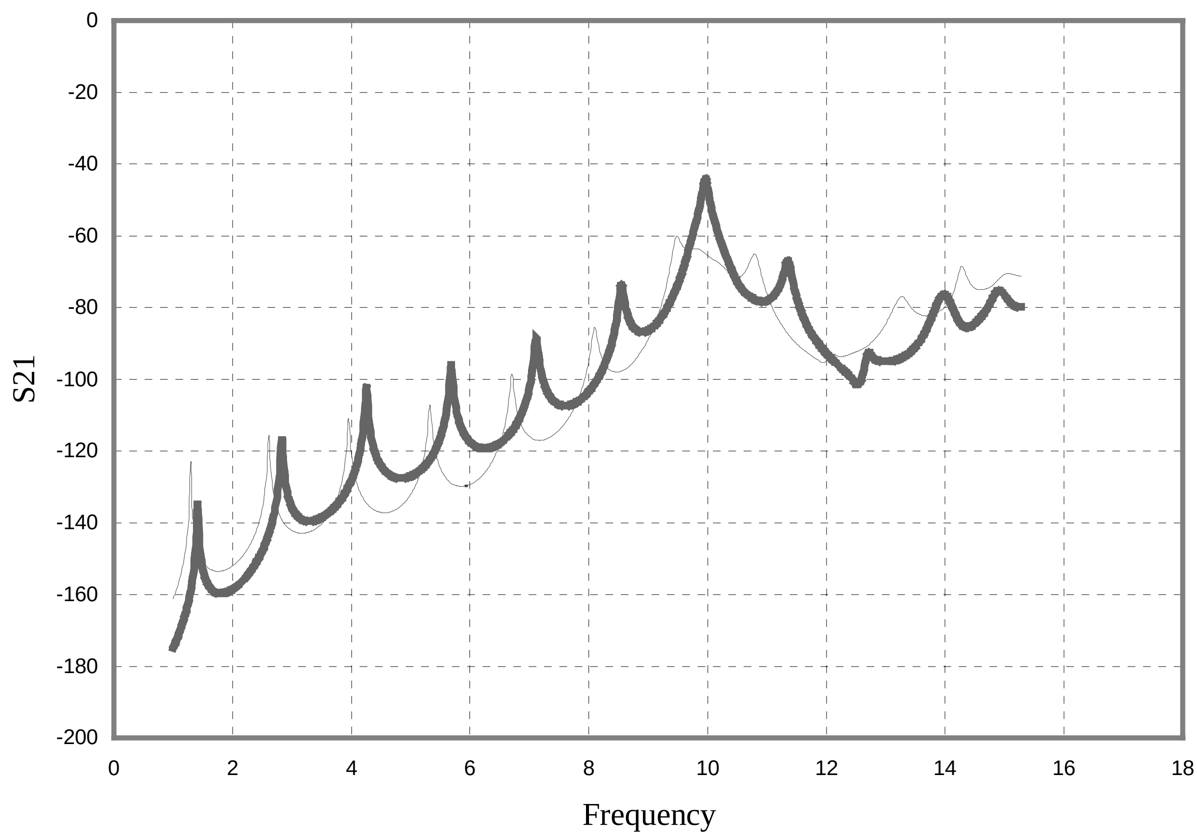


Fig B.4 Comparison between the overall S21 of the original design with different designs (132 VS 614)

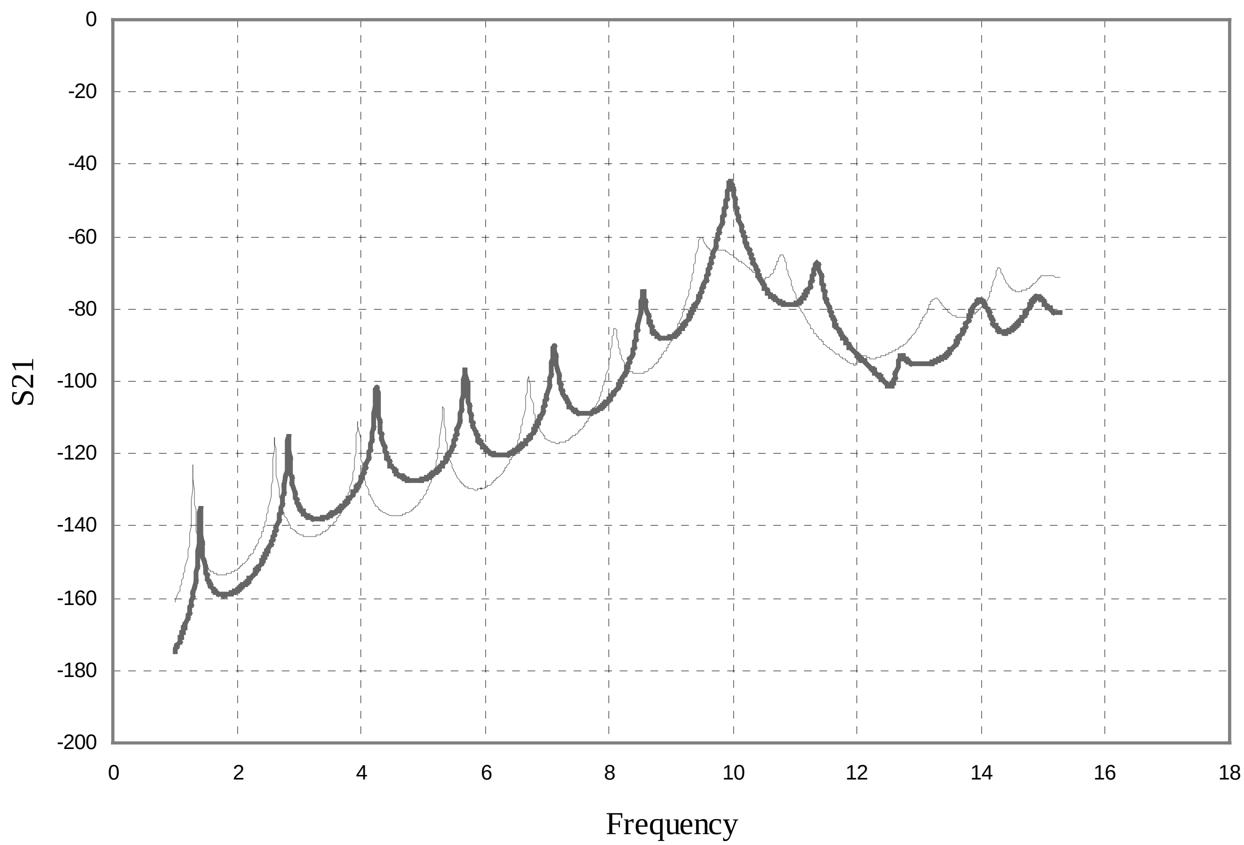


Fig B.5 Comparison between the overall S21 of the original design with different designs (132 VS 714)

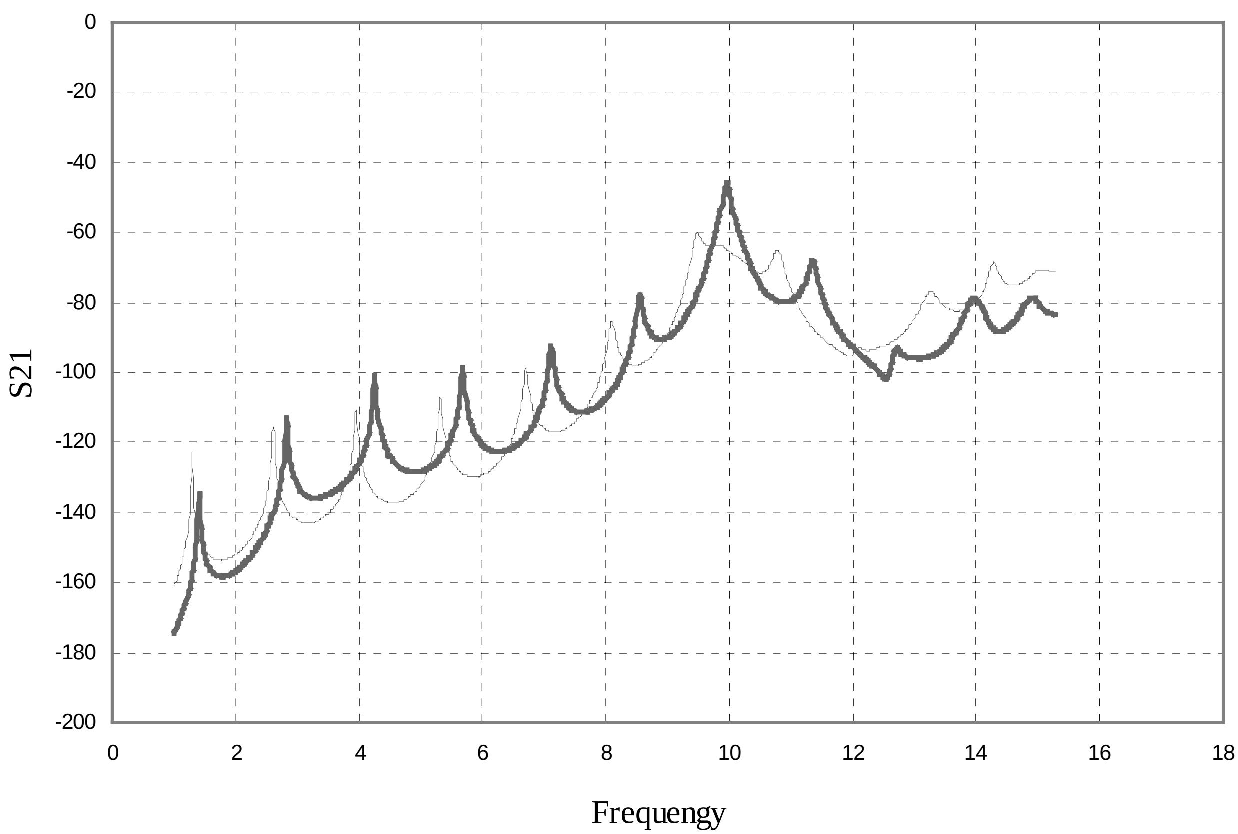
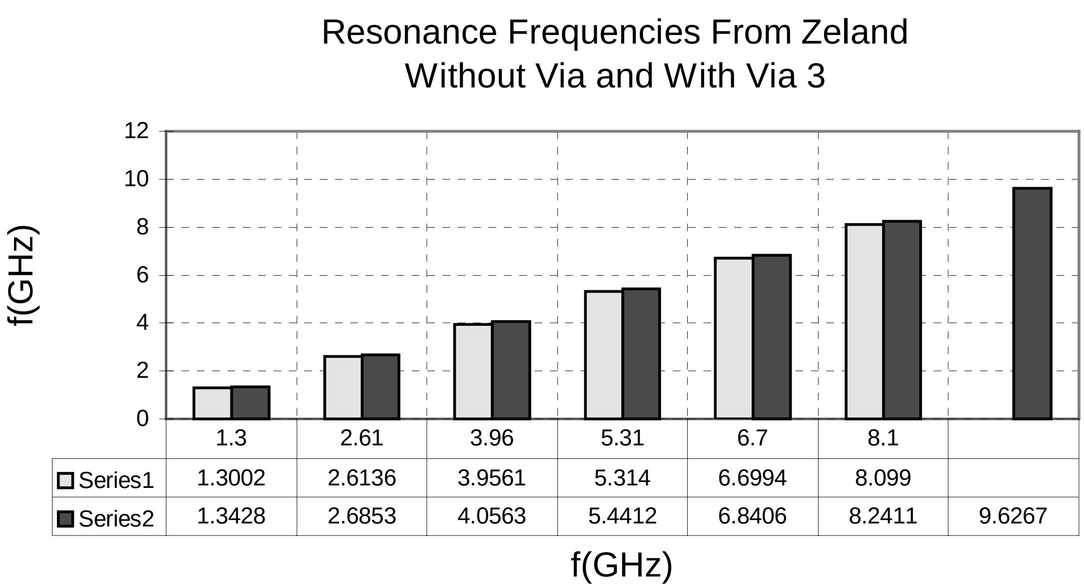


Fig B.6 Comparison between the overall S21 of the original design with different designs (132 VS 814)

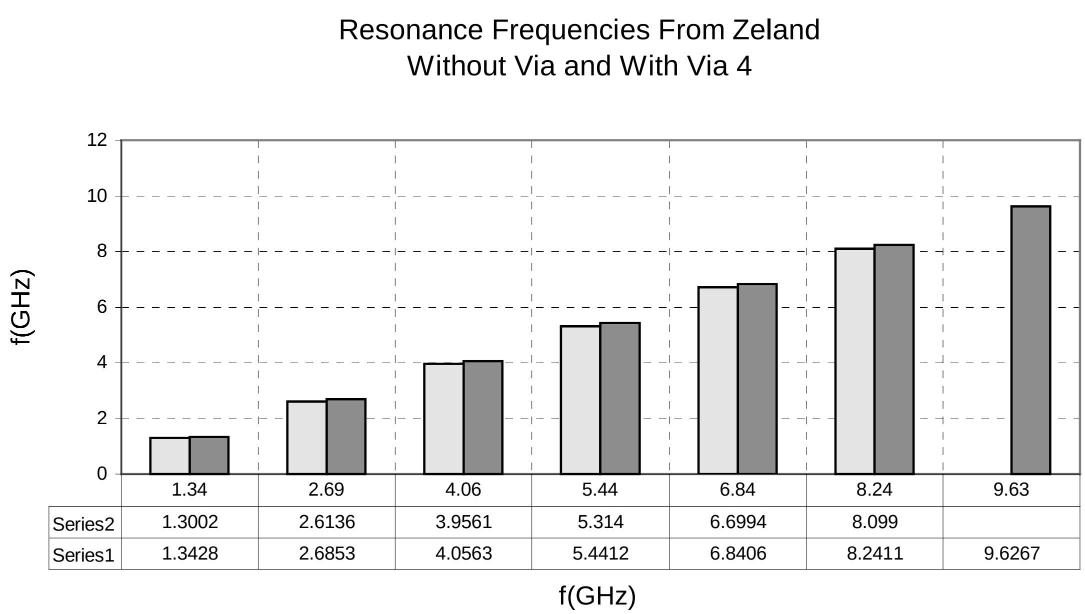
Appendix C

Comparison Between the Resonance Frequencies in Both the Original Design Without the Via and the Ones with Different Via Dimensions.



	1.3	2.61	3.96	5.31	6.7	8.1	
Series1	1.3002	2.6136	3.9561	5.314	6.6994	8.099	
Series2	1.3428	2.6853	4.0563	5.4412	6.8406	8.2411	9.6267

Fig C.1 Comparison between the resonance frequencies in both the original design and the one with via 3



	1.34	2.69	4.06	5.44	6.84	8.24	9.63
Series2	1.3002	2.6136	3.9561	5.314	6.6994	8.099	
Series1	1.3428	2.6853	4.0563	5.4412	6.8406	8.2411	9.6267

Fig C.2 Comparison between the resonance frequencies in both the original design and the one with via 4

Appendix D

Comparison Between the Relative Permitivitty in Both the Original Design Without the Via and the Ones with Different Via Dimensions Before and after using the Correction Factor.

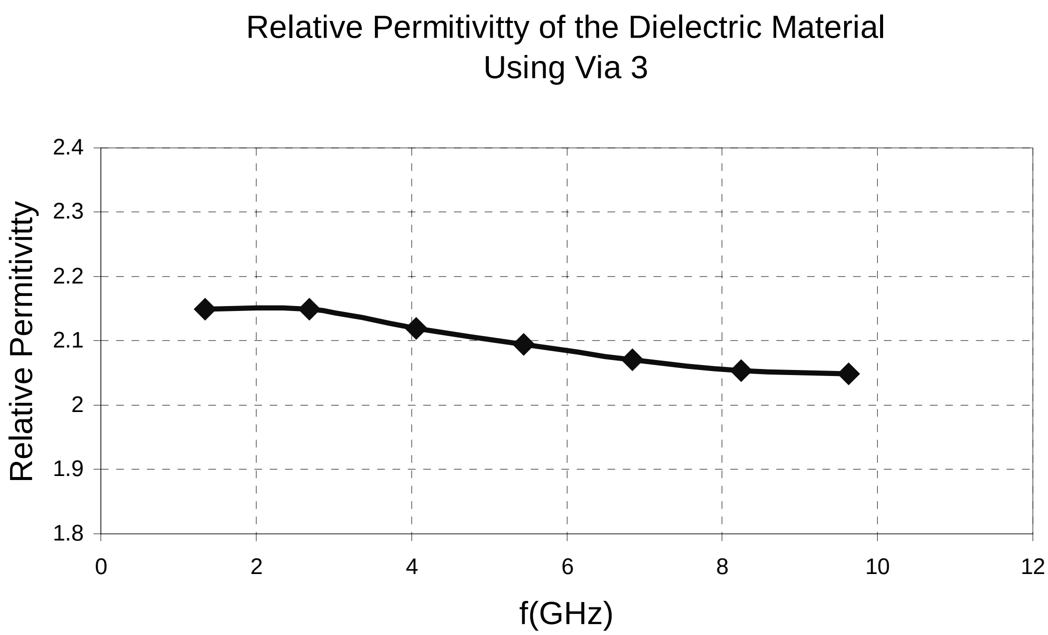


Fig D.1 The relative permittivity of the used dielectric material
using via 3

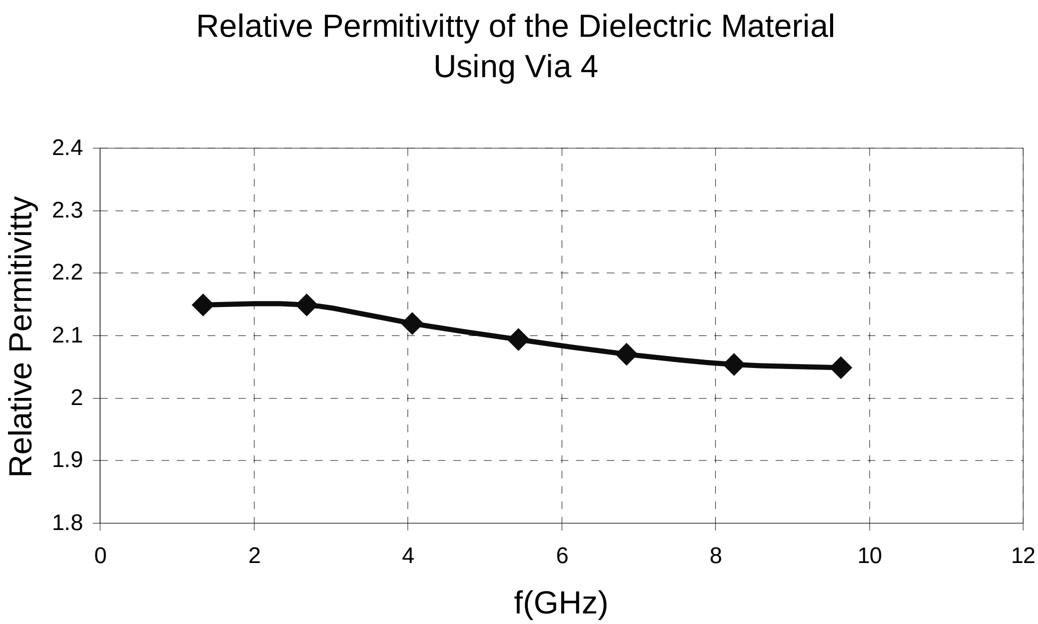


Fig D.2 The relative permitivitty of the used dielectric material
using via 4

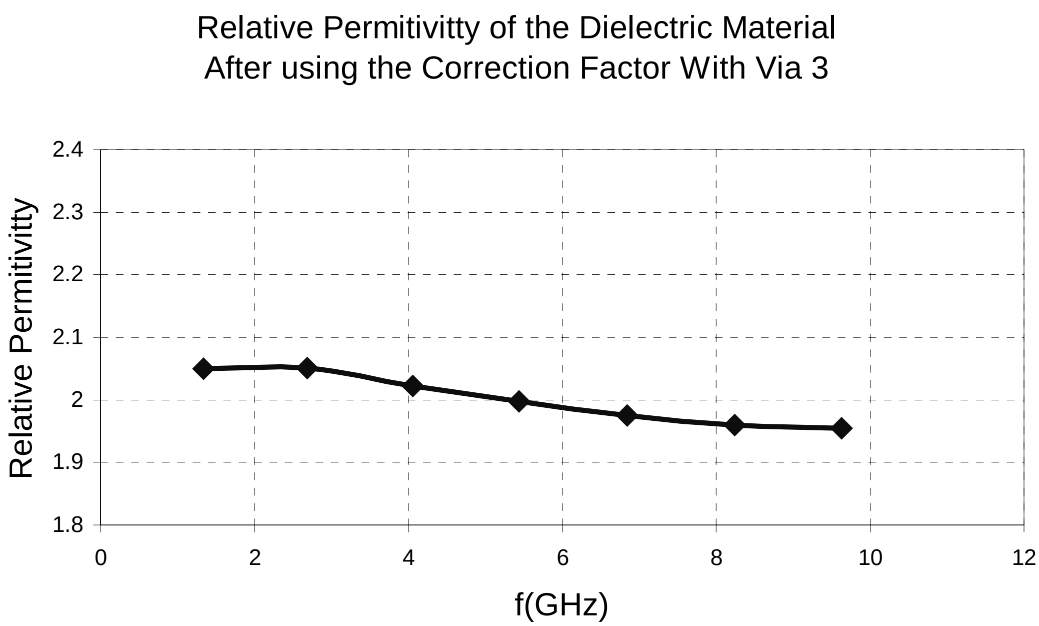


Fig D.3 The relative permittivity of the used dielectric material
After adding the correction factor with via

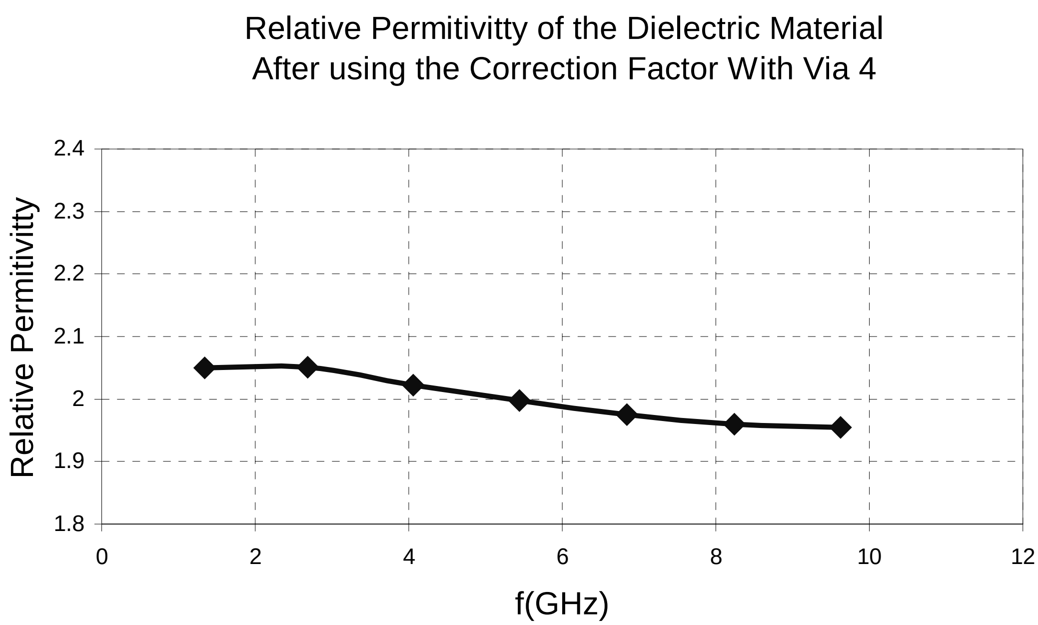


Fig D.4 The relative permittivity of the used dielectric material

After adding the correction factor with via 4

Vita

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February 1999