Progress In Electromagnetics Research, PIER 59, 39–50, 2006

A SIMPLE MODEL FOR THE ORTHOGONAL COUPLED STRIP LINES IN MULTILAYER PCB: (QUASI-TEM APPROACH)

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Abstract—In the present paper a simple model has been given to simulate the signal propagation through cross orthogonal coupled strip lines in multilayer PCB board. First the structure has been analyzed using a full wave software (such as microwave office) then a simple and suitable lumped equivalent circuit is proposed for the coupled cross talk region. The values of the lumped equivalent circuit are then obtained using a simple method. These values are then optimized to fit the S-parameters obtained using full wave analysis. Finally the s-parameters of this equivalent circuit compared with the results of full wave simulations. The results show good agreement up to some GHz.

1. INTRODUCTION

With increasing the demand to rout a lot of interconnects through a small area, the idea of multilayer structures was born. Multilayer PCB boards are used in several high frequency applications such as filter design, amplifier and so on. Multilayer boards usually designed in such a way that interconnects of one layer are orthogonal with interconnects on the two adjacent layers. This kind of structures decreases the crosstalk phenomenon between interconnects in two adjacent layers [1]. Another method to decrease coupling phenomenon is separating each set of two adjacent layers of orthogonal strips with ground planes [2].

There are a lot of classical model to analyze the coupled parallel multi conductor transmission lines on the same layer or on the different layers [2–10]. But these methods can not be used for the orthogonal line structures. In quasi-TEM mode longitudinal field of one line, although very small, has a coupling effect to the orthogonal lines on the other layers.

Some papers considered the problem of crossed lines in time and frequency domain [12, 13]. Static analysis of crossed planar multiconductor structure, has been considered in [12] using the method of lines. Also, [13] analyzed the coupled strip lines with crossed strips in frequency domain.

The problem of two orthogonal strip lines in two different layers of the PCB boards are solved using a simple equivalent model proposed in [1] for the first time. In the present paper, the problem introduced in [1] has been generalized for the arbitrary number of orthogonal interconnects in arbitrary number of layers.

For introducing the idea and for simplicity, without loss of generality, a simple structure including four orthogonal coupled strips in four layer PCB, has been considered. To analyze this structure, a suitable lumped model is given for the crosstalk region. It is assumed that there is no coupling between the strips except in the crosstalk region.

The scattering matrix of the equivalent circuit is then calculated and compared with the scattering matrix obtained from the full wave analysis. Comparison of the equivalent model results and full wave analysis shows good agreement.

2. EQUIVALENT CIRCUIT

Consider a four layer PCB structure with two strip lines in the second and third layers and two ground planes in the first and fourth layers as shown in Fig. 1.

In quasi-TEM approximation, for each line, the electric field lines are tied vertically to the ground planes and magnetic field lines in this mode are closed around the strips.

Propagation of the electric and magnetic fields can be modeled using distributed capacitance and inductance of the transmission line in form of lumped elements [4–6]. In the first approximation losses are ignored. The coupling phenomenon is appeared in arbitrary position of the lines where the lines cross each other. As an example suppose that the coupling phenomenon is appeared in the middle of the lines. We called this region "crosstalk region".

In the crosstalk region most of the electric field lines of the upper strips (third layer) are closed to each other, the upper ground (fourth layer) and down strips (second layer). Some of the E-field lines are closed to the first ground layer. There is the same for the electric field lines of the down strips.

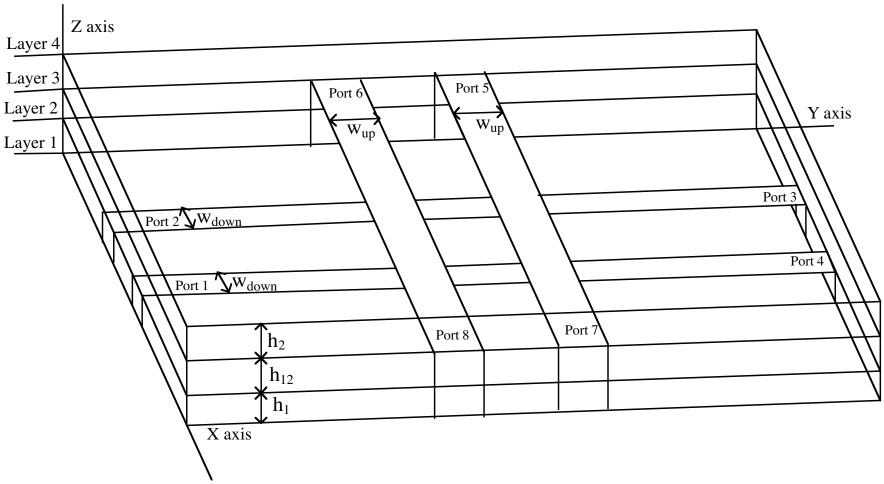

Figure 1. Four layer coplanar orthogonal strip lines.

As the first approximation, this coupling phenomenon can be modeled by mutual capacitors between the strips in the second and third layers.

To model the crosstalk region, first note that this region is too small, so the short length of the transmission lines in each layer can be modeled as two small inductors. To model the coupling phenomenon, as the first approximation, a mutual capacitance is considered between two transmission lines. So, the equivalent circuit is proposed as shown in Fig. 2.

In Fig. 2 the rectangular boxes T1, T3 represent the length of the transmission lines in four directions out of the crosstalk region. There are four crosstalk regions in this model. The crosstalk regions are modeled using lumped elements. There is one pair of coupled line between two adjacent crosstalk regions (T2, T4). It is supposed that these four sections of transmission lines have no coupling effect to each other.

3. PARAMETERS OF THE EQUIVALENT CIRCUIT

Without loss of generality, the parameters of the equivalent circuit will be obtained when both dielectric layers have the same ε_r and same height.

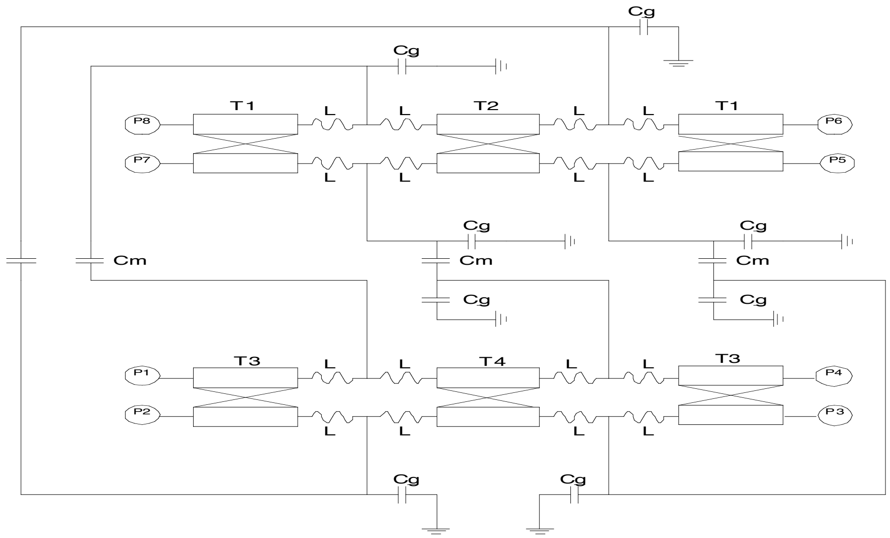

Figure 2. Equivalent circuit of four layer coplanar orthogonal coupled strip lines, shown in Fig. 1.

3.1. Ground-Capacitance of the Crosstalk Region (Cg)

For microstrip line structure the capacitance per unit length can be obtained from [5]:

$$\begin{aligned} w/h > 3 \Leftrightarrow C &= 4\varepsilon_r\varepsilon_0\left[\frac{w}{h}+\frac{2}{\pi}\ln 2\right]\text{F/m} \\ w/h < 3 \Leftrightarrow C &= 2\pi\varepsilon_r\varepsilon_0\left[\ln\left(\frac{8}{\pi}\cdot\frac{2h}{w}\right)+\frac{\pi^2}{48}\cdot\left[\frac{w}{2h}\right]^2\right]^{-1}\text{F/m} \end{aligned} \quad (1)$$

The upper strip affects the electric field distribution between the down strip and the ground plane, and this effect decreases the self capacitance of the down strip. So, this value is the first approximation of the real value in this structure. Optimized value of ground capacitances can be calculated from comparison of the scattering matrix parameters of this model and the results of full wave analysis.

3.2. Inductance

For both strips the width is much more than the thickness. If we excite strips in layer 3, the effect of the strips in layer 2 on the current distribution of the strips in layer 3 is such low that can be ignored.

Assuming current distribution of the upper strip to be uniform, one has [4]:

$$L = \frac{\mu_0}{2\pi} \cdot l \cdot \left(\ln\left(u + \sqrt{u^2+1}\right) + u \cdot \ln\left(\frac{1}{u} + \sqrt{\left(\frac{1}{u}\right)^2 + 1}\right) \right.$$
$$\left. + \frac{u^2}{3} + \frac{1}{3u} - \frac{1}{3u}(u^2+1)^{3/2} \right) H \qquad (2)$$

When $u = \frac{l}{w}$ and $l_{up} = \frac{w_{down}}{2}$. For both L_{up} and L_{down} equation (2) is used.

For increasing accuracy we separate cross region in two parts and calculate inductance for left part and right part separately.

3.3. Mutual Capacitance

With notice of field distribution, as the first approximation, the crosstalk region can be modeled by a plate capacitor with considering fringing field of the 4 sides.

So, the mutual capacitor of the cross talk region is obtained as [9, 10].

$$C_m = \frac{w_2}{h_{12}} \cdot \left(\varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}}{1 + G \cdot \left(\frac{f}{f_p}\right)^2} \right) \left(W + \frac{W_{eff} - W}{1 + \left(\frac{f}{f_p}\right)^2} \right) \qquad (3)$$

3.4. Optimizing Equivalent Circuit Parameters

The optimized values of parameters of the model in a frequency band of 0.1–3 GHz are obtained to reach the least error for all of independent s-parameters of our model in comparison with full wave analysis.

Note that in following two practical examples the optimized values are very close to the main model parameters obtained using (1)–(3).

4. PRACTICAL EXAMPLES

A substrate with $\varepsilon_r = 4.4$ is being used. For 50 ohm lines w/h ratio should be 1.951. Height of fibers h_1, h_{12} and h_2 are selected 0.615 mm and $W_{up} = W_{down} = 1.2$ mm. Both strips designed to be 50 ohm.

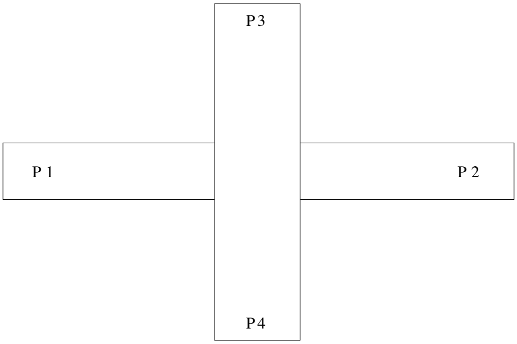

Figure 3. Two-dimensional structure of two orthogonal strip lines.

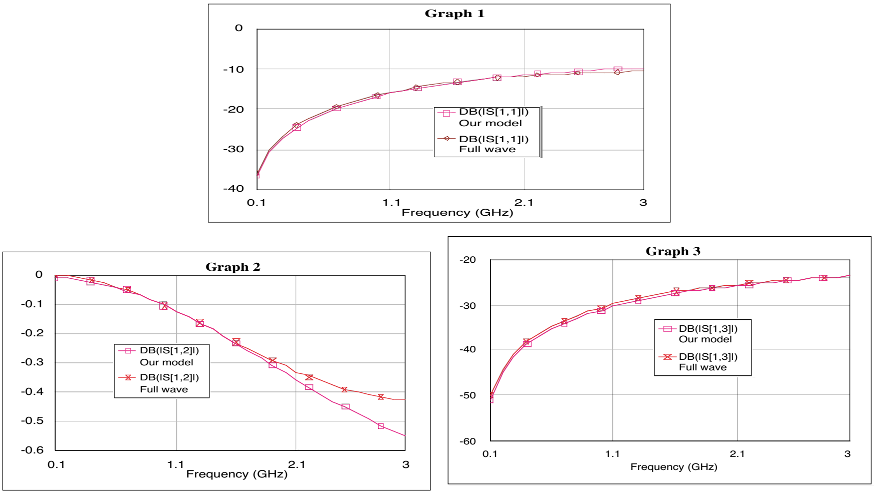

Figure 4. Comparing results of the equivalent circuit and physical structure.

4.1. Two Orthogonal Strip Lines in Four Layer PCB Board

As the first example consider two orthogonally crossed strip lines in two layers as shown in Fig. 3. Length of the both strip lines is 1 cm.

In this structure because of symmetry, only S_{11}, S_{12} and S_{13} are independent. Fig. 4 shows the results of s-parameters obtained from microwave office simulation and the s-parameters obtained from the proposed lumped model in this paper.

For this structure the parameters of the lumped model are obtained from (1)–(3) as:

$$C_{ground} = 0.2542\,\text{pF} \quad C_{coupling} = 0.25\,\text{pF} \quad L_{up} = L_{down} = 0.0874\,\text{nH}$$

The optimized parameters are obtained as:

$$C_{ground} = 0.15\,\text{pF} \quad C_{coupling} = 0.18\,\text{pF} \quad L_{up} = L_{down} = 0.0874\,\text{nH}$$

As it is clear the optimized values, are close to that obtained from (1)–(3).

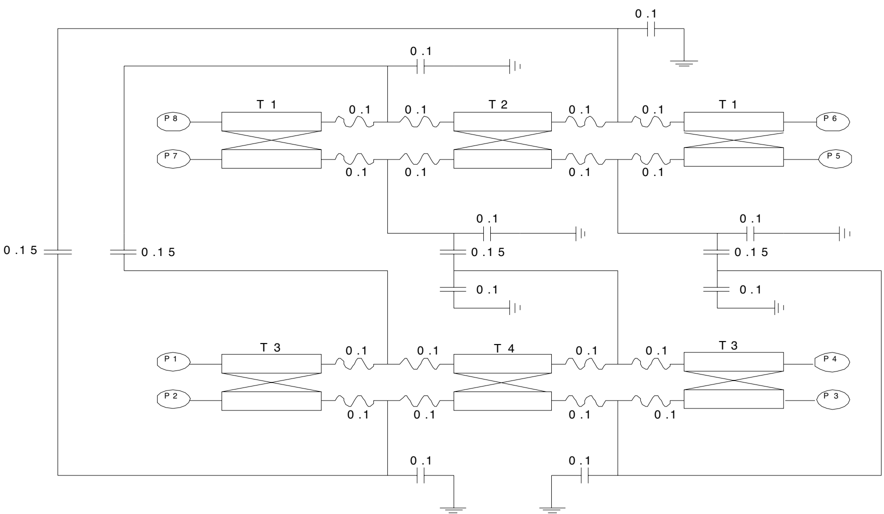

Figure 5. Equivalent circuit of two coplanar orthogonal strip lines in the crosstalk region.

The optimized parameters of this structure are obtained as:

$$C_{ground} = 0.1\,\text{pF} \quad C_{coupling} = 0.15\,\text{pF} \quad L_{up} = L_{down} = 0.1\,\text{nH}$$

Again, the optimized values are close to that obtained from (1)–(3). The percent error of some of the s-parameters is shown in Fig. 7.

4.2. Two Coplanar Orthogonal Strip Lines in Two Layer PCB Board

Another example is two coplanar orthogonally crossed strip lines as shown in Fig. 1. This structure vastly used in PCBs. Fig. 5 shows equivalent circuit model of this structure and the values of the elements. T1-T4 shown in Fig. 5 are coplanar strips with the following characteristics.

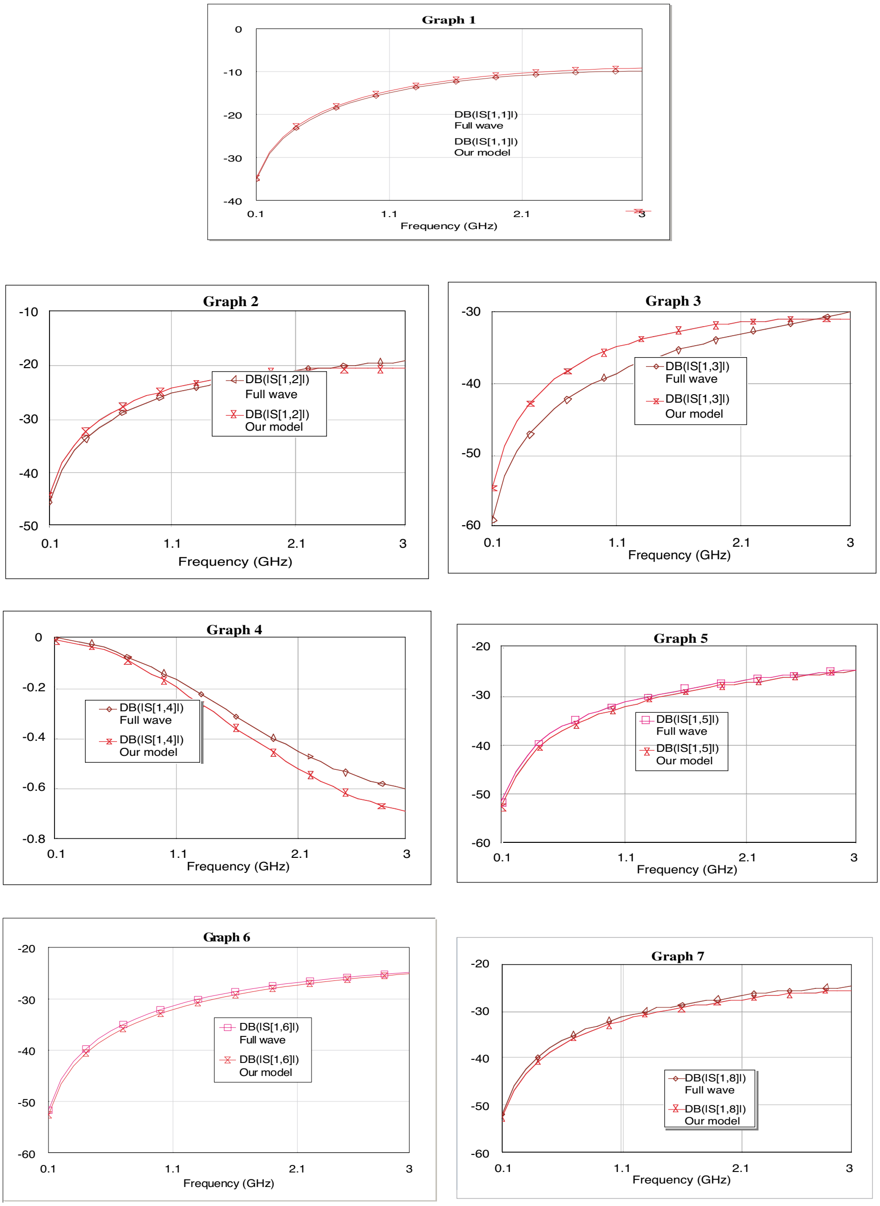

Figure 6. Comparing results of the equivalent circuit and physical structure.

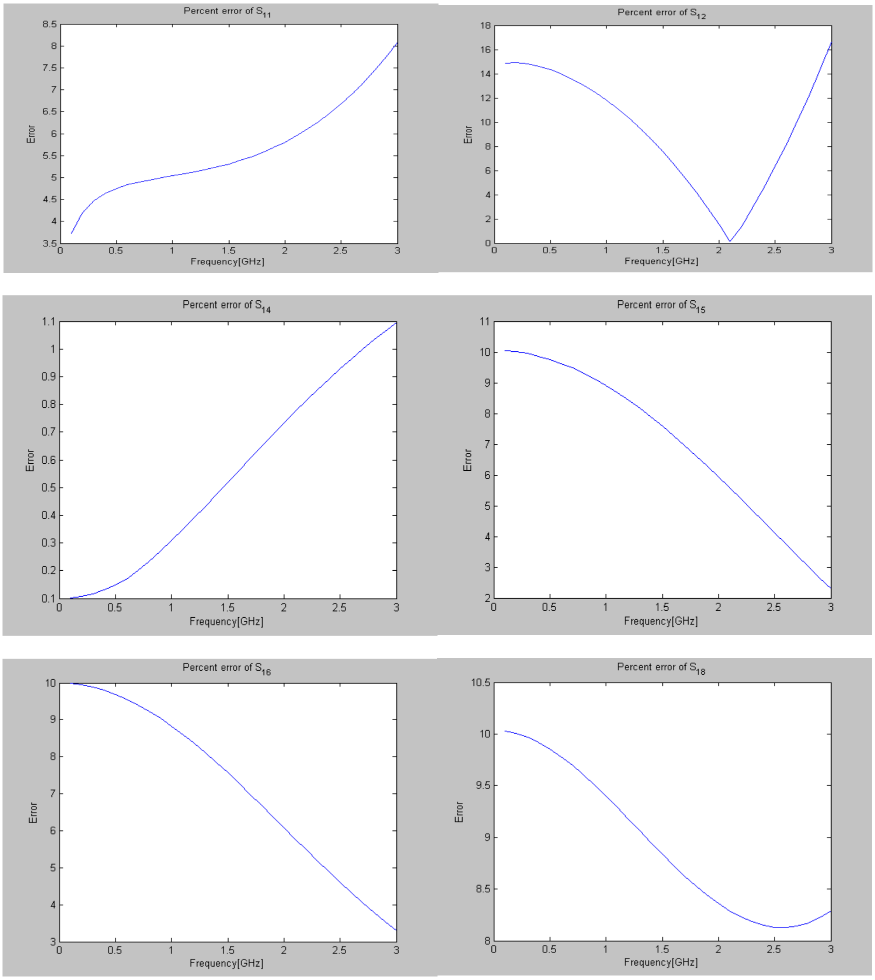

Figure 7. Error of s-parameters.

T1: gap distance = 0.4 mm, length = 4.5 mm, height of the upper dielectric = 0.615 mm, height of the lower dielectric = 1.23 mm

T2: gap distance = 0.4 mm, length = 0.8 mm, height of the upper dielectric = 0.615 mm, height of the lower dielectric = 1.23 mm

T3: gap distance = 0.4 mm, length = 4.5 mm, height of the upper dielectric = 1.23 mm, height of the lower dielectric = 0.615 mm

T4: gap distance = 0.4 mm, length = 0.8 mm, height of the upper dielectric = 1.23 mm, height of the lower dielectric = 0.615 mm

Fig. 6 shows the results of s-parameters obtained from microwave office simulation and the s-parameters obtained from the proposed lumped model in this paper. Because of symmetry, in this structure, $S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}$ and S_{18} are independent.

To see the behavior of the proposed model in higher frequency band, the s-parameters of our model is being compared with those obtained from full wave analysis up to 30 GHz. Some of the results are shown in Fig. 8.

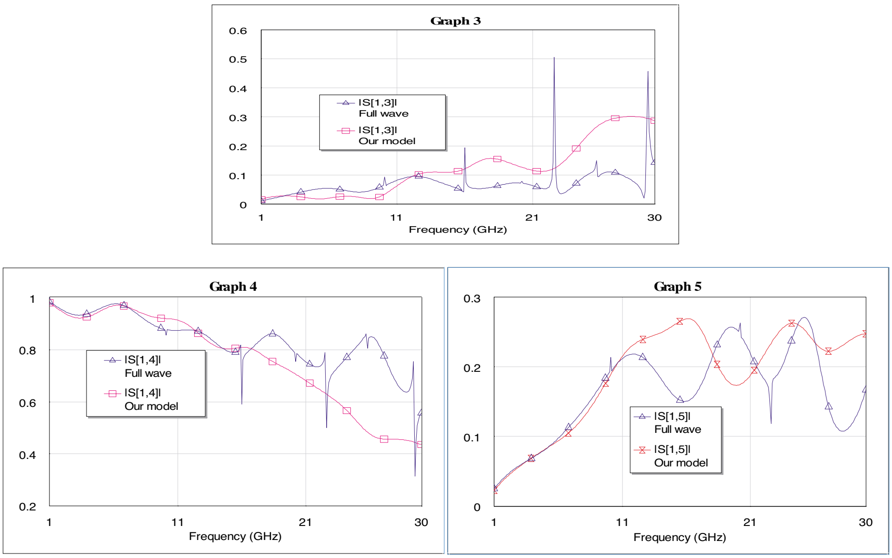

Figure 8. Behavior of our model in frequency band up to 30 GHz.

As it is clear the results of this method up to the first resonance of the cavity resulted from the upper and lower ground planes is close to the results of full wave analysis. Resonant frequency $(f_c)_{101}^{TE}$ of the cavity is 10.108 GHz, which can be obtained simply using traditional field analysis [11].

$$(f_c)_{mnp}^{TE} = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} \quad m = n \neq 0 \qquad (4)$$

5. CONCLUSION

In this paper a simple model is given to analyze the crossed orthogonal coupled strip lines in multilayer PCB. The cross talk region is modeled, as the first approximation, using simple lumped elements. The results show, as expected, that the crosstalk signal from one layer to the second layers is very small compared to the transmitted signal. The proposed model only considers the quasi-TEM part of the waves. So, the proposed equivalent circuit can be used to model the physical structure from the terminals point of views (S-parameters, Z-parameters, etc).

The results of this method show good agreement with those obtained from full wave analysis up to the first resonance of the cavity.

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