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SIMPLE AND NOVEL MODEL FOR EDGED MICROSTRIP LINE (EMTL)

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Abstract—In this paper a simple model has been introduced to simulate the propagation of signal in a so called edged microstrip transmission line (EMTL). EMTL is a transmission line in which the signal strip is laid on the edge of the structure (Fig. 1).

First a simple structure of EMTL is modeled with an ordinary MTL with improved per unit length inductances and capacitances, and an additional resistance to represent the radiation from the edges. This method is then applied to model a multilayer cross orthogonal EMTL structure as shown in Fig. 2.

The model is finally validated using full wave analysis simulator, HFSS. The S-parameters of our model show good agreement with the results of the full wave analysis (HFSS) up to some GHz.

1. INTRODUCTION

Microstrip transmission lines (MTLs) have received much consideration in the technical literature in the last 40 years. Most of the efforts were dedicated to the analysis and electrical characterization of single or coupled microstrip lines. Recently, the request to fabricate PCB's with more interconnections in a small area has been increased. Therefore the idea of multilayer structures was born.

There are a lot of classical models to analyze simple transmission lines and so parallel coupled multiconductor lines on the same layer or on the different layers [1–5]. Orthogonal strip lines decrease coupling between lines in two different layers. The problem of crossed lines in time and frequency domain has been considered in [12, 13]. Static analysis of crossed planar multiconductor structure has been examined in [12] using the method of lines. Also, [13] analyzed the coupled strip lines with crossed strips in frequency domain. Also a new model was introduced for two crossed orthogonal coupled strip lines in [6]. This idea was generalized in [7] for the arbitrary number of orthogonal interconnects in arbitrary number of layers.

Some of the transmission lines in PCB lie on the edge of ground plane of PCB. This structure increases radiation from the line and so changes the capacitance and inductance per unit length of the line.

In the present paper first a simple method is introduced to model EMTL as an ideal microstrip line. The effect of the radiation from the edges is modeled as radiation resistance. Then this model is used to simulate the behavior of crossed orthogonal coupled EMTL in three different layers from terminals point of view. We also should note that it is necessary to use lumped elements, in order to simulate cross talk region of orthogonal coupled structures.

Finally S-parameters of optimized equivalent circuit are calculated and compared with those obtained from full wave analysis (HFSS). The results show good agreement up to some GHz.

2. EQUIVALENT MODEL OF EMTL

As basic and main part of this paper, a microstrip transmission line laid on the edge of ground plane is considered (Fig. 1). It is obvious that capacitance and inductance per unit length of this microstrip line is different from those of a microstrip in the middle of the structure. When line is not in the middle of ground plane, there is some radiation from edge of the line. From terminals point of view, this radiation can be modeled with a resistance called as radiation resistance.

There are many formulas for capacitance and inductance per unit length of ideal microstrip and strip lines [8–11]. In the present paper we use following expression for the capacitance of ideal microstrip (C_i) from [11]:

$$C_i = \frac{[(1+\varepsilon_g)^2/4\varepsilon_g]C_a(H_e)}{1 + C_a(H_e)\displaystyle\sum_{m=1}^{M} \eta^m \frac{1}{C_a[(m+1)H_e]}} \tag{1}$$

Corresponding to the literature H_e is the equivalent substrate thickness, $\eta = \frac{1-\varepsilon_g}{1+\varepsilon_g}$ and $\varepsilon_g = \sqrt{\varepsilon_r \varepsilon_y}$ which in the case $\varepsilon_y = \varepsilon_r$, we have $\varepsilon_g = \varepsilon_r$. Also, C_a is the capacitance per meter of a strip above a ground plane with air dielectric.

In [10] there are some formulas for components of capacitance per unit length of a microstrip line. Fig. 2 shows these components and so

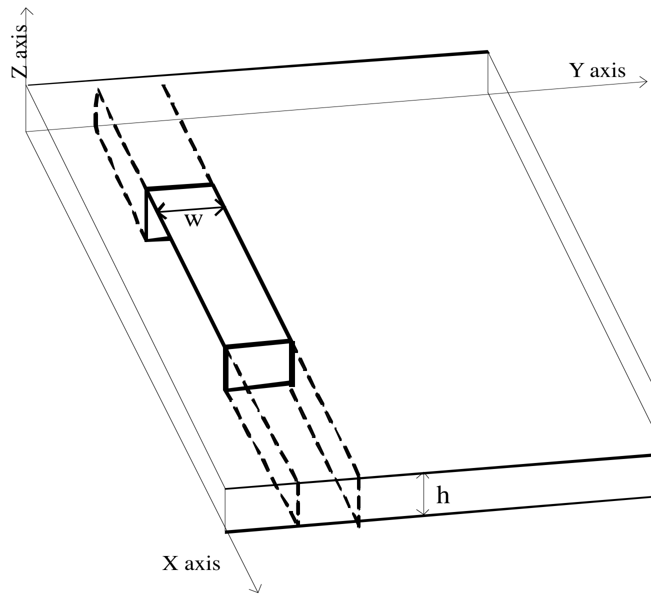


Figure 1. Structure of EMTL.

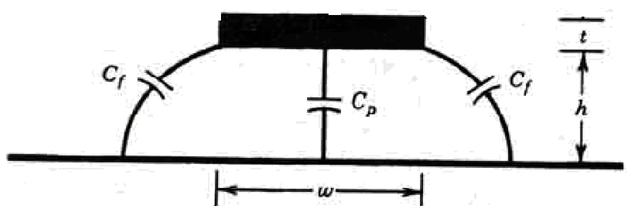


Figure 2. Capacitance model for stripline transmission line [10].

the per unit length capacitance of EMTL (C_e) can be obtained as:

$$C_e = C_i - C_f - \frac{C_i - C_p - 2C_f}{3} \tag{2}$$

C_p is the capacitance between two parallel plates and C_f is the fringing capacitance.

The capacitance of an ideal microstrip transmission line (C_i), consists of the capacitance coupled between the upper and lower surfaces of the strip and the ground plane. The lower capacitance is the sum of one C_p component and two C_f components that are coupled between the lower surface of the strip and the ground plane. There is also a small portion of capacitance which is coupled between upper surface of strip and the ground plane shown with $C_i - C_p - 2C_f$.

To illustrate the origination of expression 2, we need to demonstrate the two fundamental differences between the capacitance of the ideal microstrip line and that of EMTL. The first difference is a fringing capacitance (C_f) which is directly related to the edged fringing phenomena. The second difference is best demonstrated by dividing the upper surface of strip to three regions. Our assumption to reach expression 2 is that the edged part of upper surface can not couple its capacitance with ground plane. Therefore the terms C_f and $\frac{C_i - C_p - 2C_f}{3}$ must be subtracted from C_i.

With same strategy, inductance per unit length of ideal microstrip (L_i) can be obtained simply using classical formulas of electromagnetic.

$$L_i = \frac{1}{c^2 C_i} \tag{3}$$

In this formula, c is the velocity of wave in free space. Assuming that $\mu_r = 1$, the inductance per unit length of the "ideal line" (L_i) can be used instead of that of the "edged line" (L_e).

In this stage we must attribute a per unit resistance to EMTL simulating the radiation from edge. The main goal of this paper is to model a non-ideal EMTL with an ideal MTL which is usable by such simulator software as HSpice. Therefore assuming that there is no radiation resistance in DC frequency, a skin effect resistance will be obtained by means of which we can minimize the square error between scattering matrix of model and full wave analysis. We simulate this resistance with following formula:

$$R(f) = R_o + \sqrt{f}(1 + j)R_s \tag{4}$$

R_o is the DC resistance which is zero and R_s is the skin effect resistance. In order to obtain a proper mode we need to optimize R_s.

What is important here is that, the radiation resistance for a determined value of dielectric constant is just a function of the ratio of strip width (w) to height of the dielectric (h). Fig. 3 shows this resistance for both MTL and EMTL with dielectric constant equal to 4.4 as a function of w/h.

After optimizing values of capacitance and inductance, regardless of the possible radiation resistance, we compare the scattering matrix of this model with the matrix obtained from HFSS simulation. They do not show good agreement, especially for frequencies above 6 GHz. Table 1 shows calculated and optimized values of capacitance and inductance per unit length of EMTL's. It is possible to present an accurate model because the calculated and optimized parameters show good agreement.

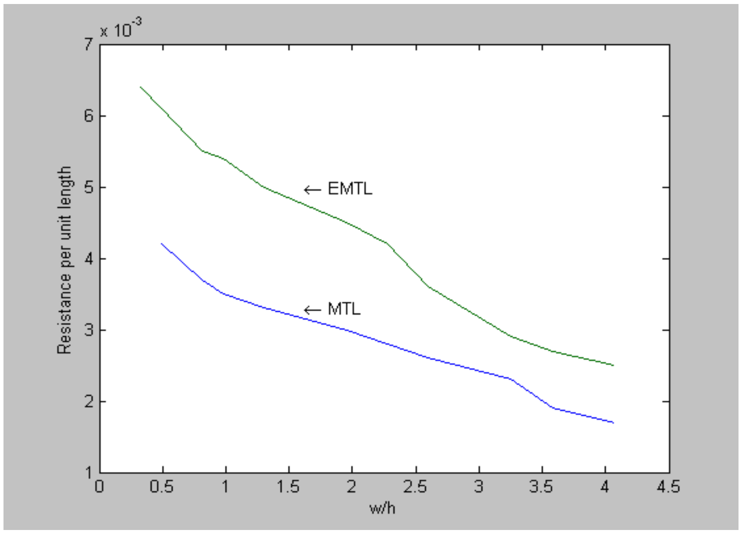


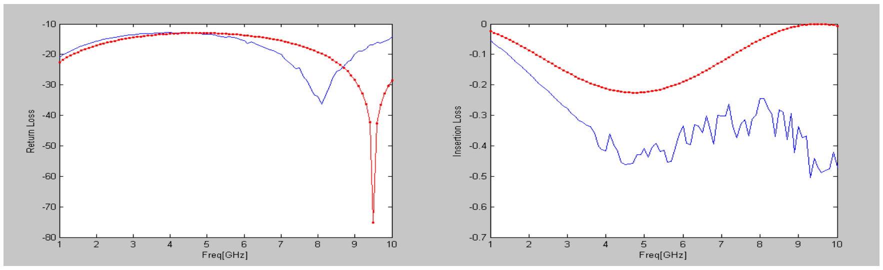
Figure 3. Radiation resistance for MTL and EMTL as a function of w/h.

Table 1. Calculated and optimized C and L of lines.

w/h ratio	C (Calculated)	C (Optimized)	L (Calculated)	L (Optimized)
0.813	55.4	59.8	460.96	463
0.976	62.4	66	426.3	426
1.301	76	78	372.85	372
2.276	115.5	124	276.19	277
2.602	129	132	254.83	254
3.252	155	158	221.17	221
3.577	169	173	207.64	208
4.065	189	191	190.34	190

Fig. 4 shows some of these results for different values of w/h ratio. From the figures below it is obvious we still need to reach a better model.

To show advantages of our proposed model, we add radiation resistance (Fig. 3) to that. Now we can compare S-parameters of equivalent model with HFSS simulation. Fig. 5 shows some of these diagrams for different values of w/h ratio. We tested our model from terminals point of view, and we used several terminal ports (various ohmic resistances) for any EMTL to show the radiation resistance is independent from terminal port.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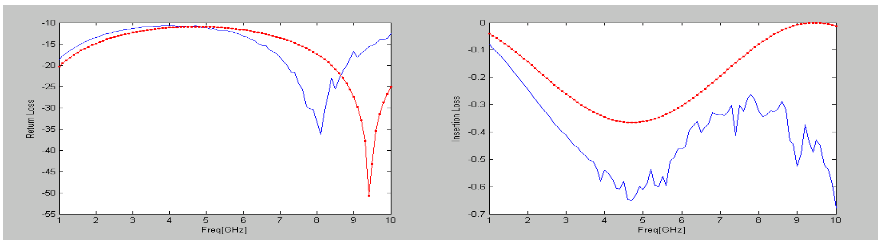
(a)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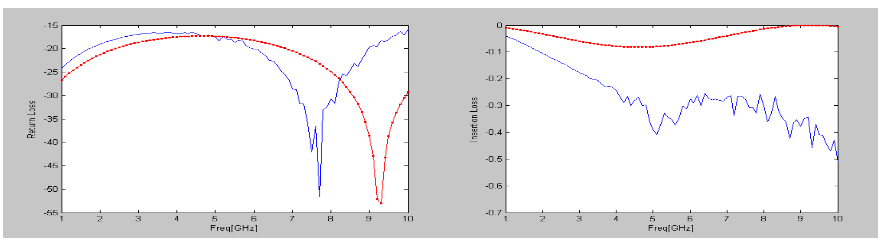
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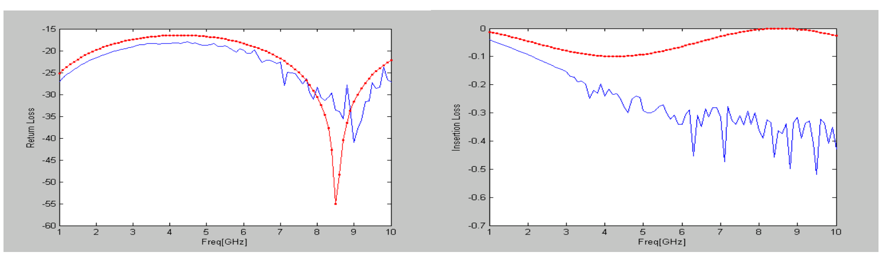
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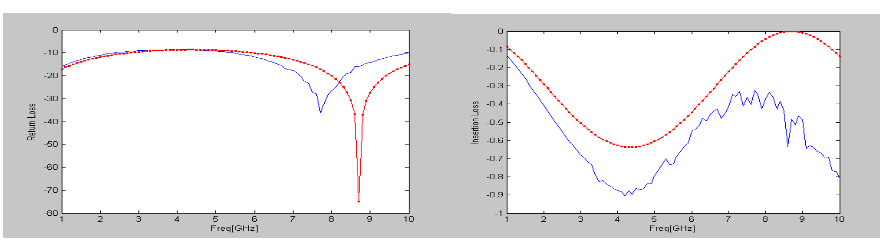
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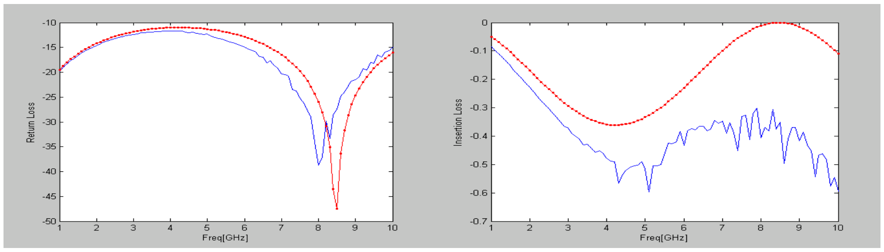

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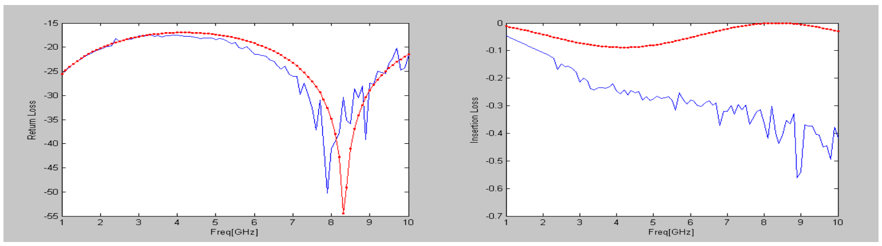

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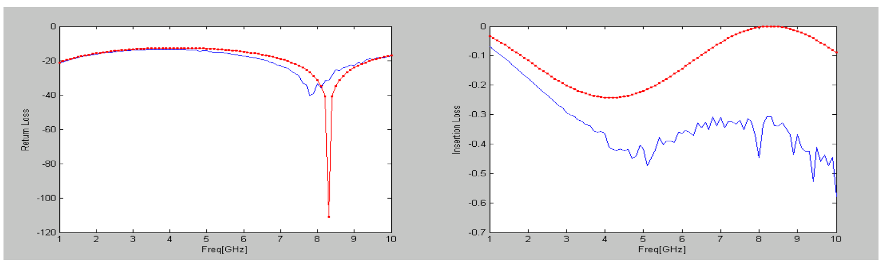
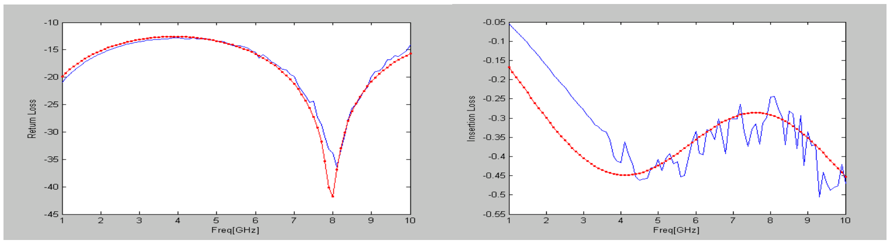


(h)

Figure 4. The comparison of scattering matrix of the model, regardless of the radiation resistance, with HFSS simulation. $w/h =$ (a) 0.813 (b) 0.976 (c) 1.301 (d) 2.276 (e) 2.602 (f) 3.252 (g) 3.577 (h) 4.065.

3. THREE LAYERS STRUCTURE OF EMTL

This is a common technique to use ground planes between layers of a multilayer PCB in order to decrease the coupling. A good alternative is orthogonal coupled microstrip lines. This structure is amongst the most widely used structures in microwave devices, especially in PCB's. Orthogonal coupled microstrip line is discussed in [6, 7] and an accurate model is also introduced. This structure is discussed in [6, 7] and an accurate model is also introduced. Now we can develop this idea to recommend a model for edged orthogonal coupled microstrip line shown in Fig. 6. in this figure, $w = 1.6$ mm, $h = 0.615$ mm and the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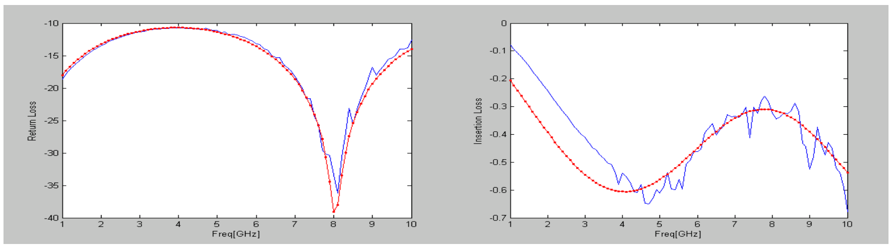
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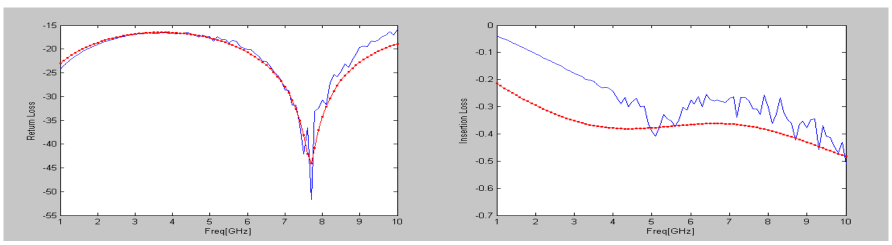
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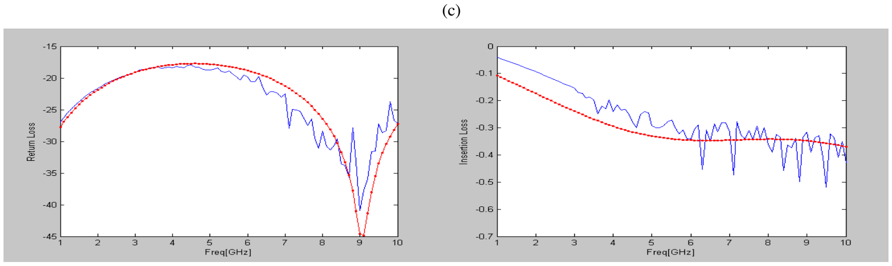
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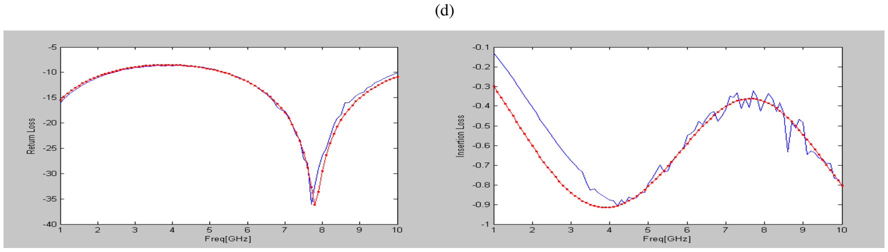
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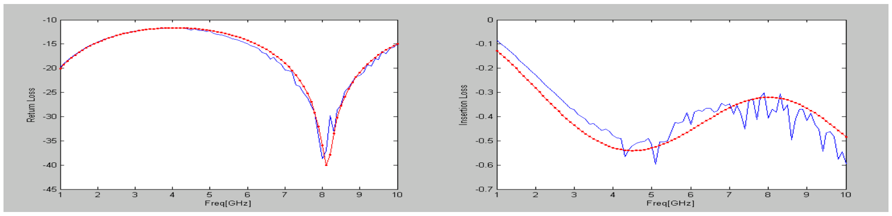

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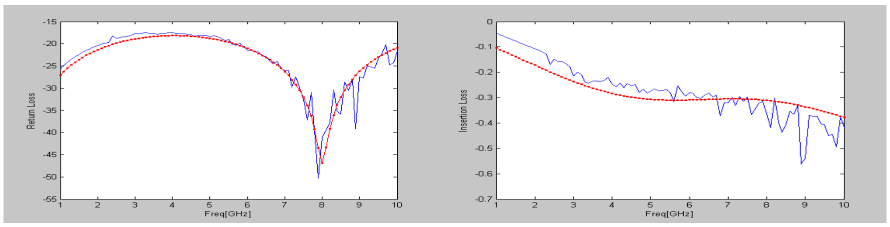

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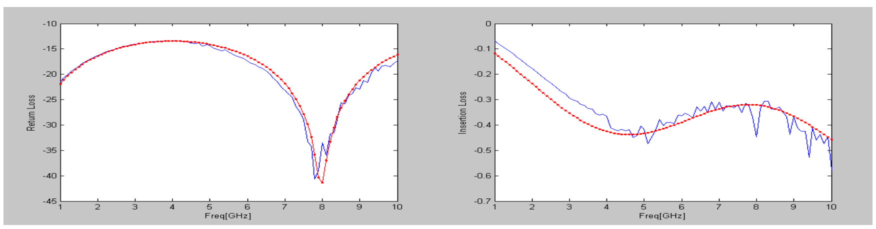

(h)

Figure 5. Comparison of scattering matrices of proposed model with HFSS analysis. $w/h =$ (a) 0.813 (b) 0.976 (c) 1.301 (d) 2.276 (e) 2.602 (f) 3.252 (g) 3.577 (h) 4.065.

length of lines is 10 mm with terminal ports of $50\,\Omega$. The dielectric constant is equal to 4.4. For these two transmission lines, the resistance introduced before, is obtained from Fig. 3.

When two lines cross each other (cross talk region), this region can be modeled with lumped elements, based on [6, 7]. Fig. 7 shows a simple scheme of this model. C_{12} represents coupling between lines and the effect of cross talk region length is shown with four inductances. C_g represents the capacitance between lower line and ground plane. Values of these elements are obtained with following formulas.

$$C_g = 2\pi\varepsilon_r\varepsilon_0 \left[\ln\left(\frac{8}{\pi}\cdot\frac{2h}{w}\right) + \frac{\pi^2}{48}\left(\frac{w}{2h}\right)^2\right]^{-1} \text{ F/m} \tag{5}$$

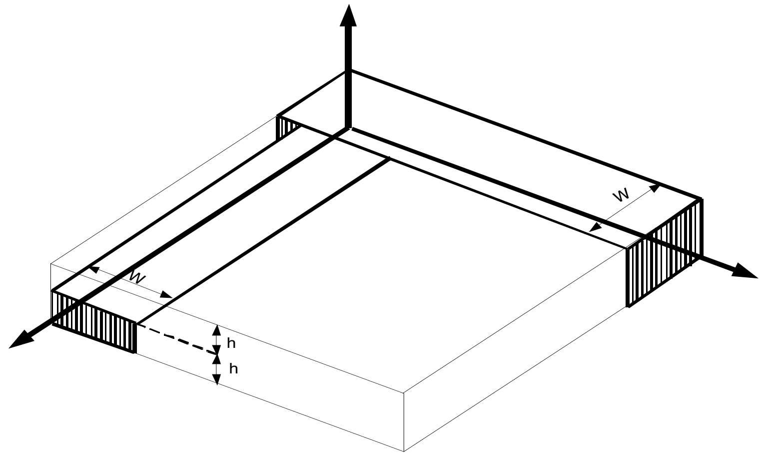

Figure 6. Edged coupled microstrip line.

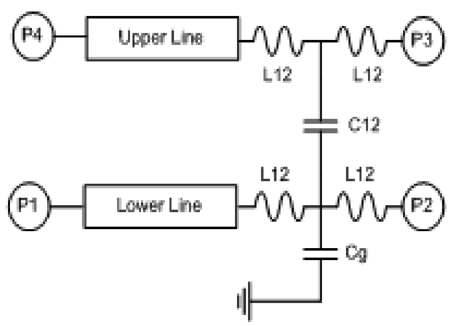

Figure 7. The proposed model of edged coupled microstrip line.

$$L_{21} = \frac{\mu_0}{2\pi} \cdot l \cdot \left(\ln\left(u + \sqrt{u^2+1}\right) + u \cdot \ln\left(\frac{1}{u} + \sqrt{\left(\frac{1}{u}\right)^2 + 1}\right) + \frac{u^2}{3} + \frac{1}{3u} - \frac{1}{3u}(u^2+1)^{3/2} \right) \text{ H} \tag{6}$$

$$C_{12} = \frac{w}{h}\varepsilon_0 \cdot \left(\varepsilon_r - \frac{\varepsilon_r - \varepsilon_{reff}}{1 + G \cdot \left(\frac{f}{f_p}\right)^2} \right) \left(W + \frac{W_{eff} - W}{1 + \left(\frac{f}{f_p}\right)^2} \right) \text{ F} \tag{7}$$

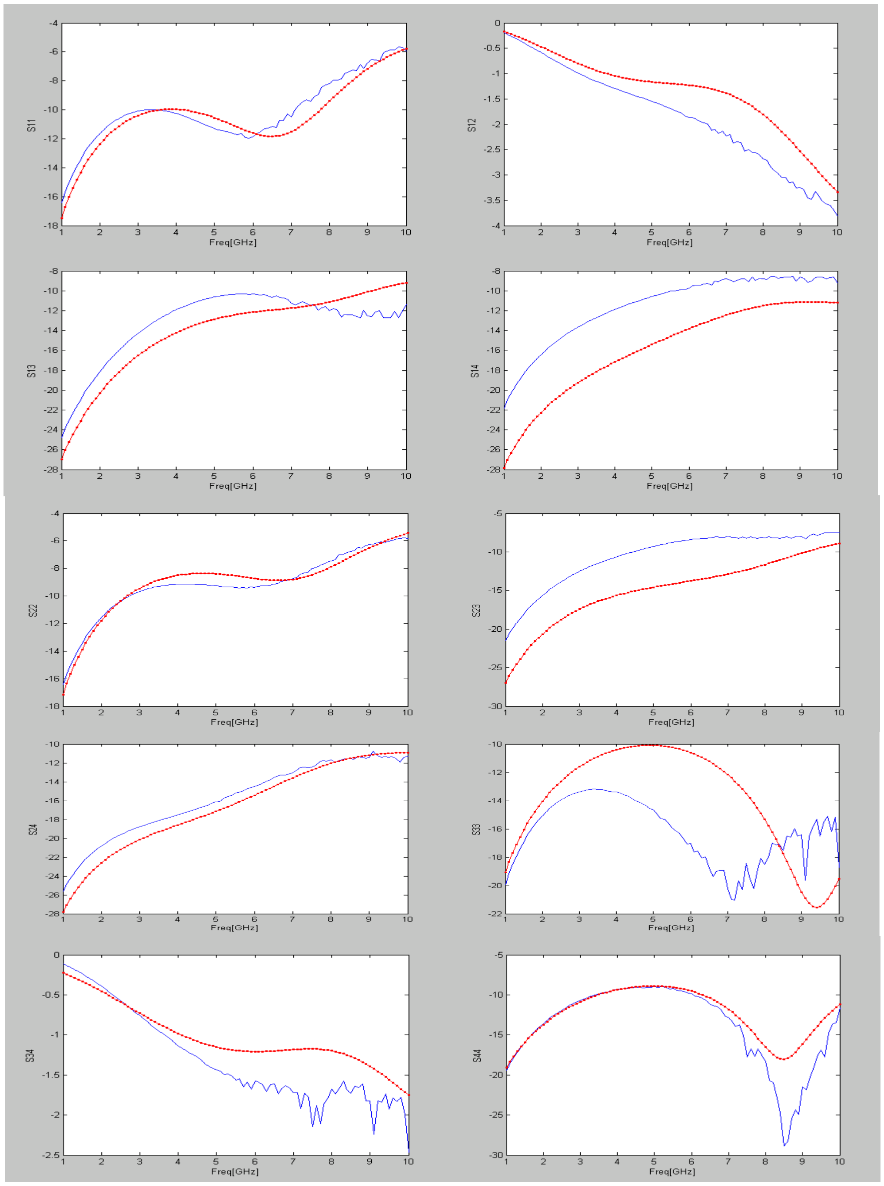

Figure 8. Comparison of HFSS simulation with our model of edged coupled microstrip line.

Parameters $u, l, \varepsilon_{reff}, W_{eff}, G$ and f_p in these formulas are explained in [6]. Based on mentioned calculations, we have:

Upper Line: $C = 78\,\mathrm{pF/m}$, $L = 372\,\mathrm{nH/m}$, $R_s = 0.0052\,\Omega/\mathrm{m}\sqrt{\mathrm{s}}$

Lower Line: $C = 132\,\mathrm{pF/m}$, $L = 254\,\mathrm{nH/m}$, $R_s = 0.0036\,\Omega/\mathrm{m}\sqrt{s}$

$C_g = 0.38\,\mathrm{pF}$, $C_{12} = 0.3\,\mathrm{pF}$, $L_{12} = 0.163\,\mathrm{nH}$

Now we can compare the HFSS solution with the proposed model solution. After optimizing the parameters of model, scattering matrix of model is obtained. Fig. 8 shows scattering parameters of HFSS simulation and that of our model. The optimized parameters of model are as follows:

Upper Line: $C = 81\,\mathrm{pF/m}$, $L = 373\,\mathrm{nH/m}$, $R_s = 0.0052\,\Omega/\mathrm{m}$

Lower Line: $C = 157\,\mathrm{pF/m}$, $L = 240\,\mathrm{nH/m}$, $R_s = 0.0036\,\Omega/\mathrm{m}$

$C_g = 0.38\,\mathrm{pF}$, $C_{12} = 0.27\,\mathrm{pF}$, $L_{12} = 0.16\,\mathrm{nH}$

We should mention, in Fig. 8 the difference observed between our proposed model and the full wave analysis (for some S-parameters below 10 dB) is due to round off error. Since these values are considerably small, our model will still show good agreement with full wave analysis.

4. CONCLUSION

In this paper a simple model is presented to analyze the microstrip line laid on the edge of ground plane. This structure is modeled with an ideal line to which a per unit length radiation resistance is added.

We optimize the parameters of EMTL in order to minimize the square error between scattering matrix of model and HFSS analysis. Optimized values of capacitance and inductance are in a very good agreement with those values obtained from analytical formulas.

Fig. 5 shows that our model can be used instead of EMTL. Fig. 3 shows that the radiation resistance of proposed model is nearly linear, versus w/h ratio.

This model can be used to model more complicated structures like crossed orthogonal coupled EMTL. Cross talk region in this structure is modeled with some lumped elements. We showed that our proposed model can be used to design multilayer microstrip lines with a good accuracy.

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