Quasi-TEM Analysis of Multilayer Coplanar Waveguide Broadside Coupled Lines Balun

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***Abstract*- The accurate estimates of values of electromagnetic parameters are essential to determine the final circuit speeds and functionality for designing of high-performance integrated circuits and integrated circuits packaging. In this paper, the quasi-TEM analyses of multilayer coplanar waveguide (CPW) broadside coupled-line balun are successfully demonstrated using Finite Element Method (FEM). We specifically determine the capacitance and inductance matrices and the quasi-static spectral for the potential distribution of the developed integrated circuit.**

Keywords- finite element method; capacitance;, inductance; IC interconnect; CPW transmission lines

I. INTRODUCTION

The designing of fast electronics circuits and systems with increase of the integration density of integrated circuits has led to wide use and cautious analysis of CPW broadside coupled-line balun. For example, a triple coupled CPW can be used for microwave applications as couplers for combining two independent signals [1] and as basis building blocks [2, 3]. The matrices of capacitances per unit length of CPW transmission line are known as the essential parameters in designing of package, lossless transmission line system, microwave circuits, printed circuit board (PCB), multichip modules (MCM) design and high speed very large scale integration (VLSI) circuits. Therefore, the improvement of accurate and efficient computational method to analyze quasi-TEM transmission lines structure becomes an important area of interest. Also, to optimize the electrical properties of the integrated circuits, the estimate of the capacitance matrix of multilayer and multiconductor interconnects in VLSI circuit must be investigated. The computational values of self and coupling capacitance can also help engineers and designers to optimize the layout of the circuit [4]. There are previous attempts at the problem. These include using the conformal mapping method [5], the spectral domain method [6], the potential integral formalization method [7].

In this work, we design electrostatic model CPW broadside coupled-line balun using the FEM. Many industrial applications depend on different interrelated properties or natural phenomena and require multiphysics modeling and simulation as an efficient method to solve their engineering problems. Moreover, superior simulations of microwave integrated circuit applications will lead to more cost-efficiency throughout the development process. In this article, we specifically calculate the capacitance and inductance matrices and the potential distribution of the configuration.

II. RESULTS AND DISCUSSIONS

The models are designed in two-dimensional (2D) using electrostatic environment in order to compare our results with some of the other available methods. In the boundary condition of the model's design, we use ground boundary which is zero potential ($V=0$) for the shield. We use port condition for the conductors to force the potential or current to one or zero depending on the setting. Also, we use continuity boundary condition between the conductors and between the conductors and left and right grounds.

The quasi-static models are computed in form of electromagnetic simulations using partial differential equations. For coupled multiconductor transmission lines, it is convenient to write:

$$Q_i = \sum_{j=1}^{m} C_{sij} V_j \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{m}) \quad , \qquad (1)$$

where Q_i is the charge per unit length, V_j is the voltage of j th conductor with reference to the ground plane, C_{sij} is the short circuit capacitance between i th conductor and j th conductor. The short circuit capacitances can be obtained either from measurement or from numerical computation. From the short circuit capacitances, we obtain

$$C_{ii} = \sum_{j=1}^{m} C_{sij} \qquad (2)$$

where C_{ii} is the capacitance per unit length between the i th conductor and the ground plane. Also,

$$C_{ij} = -C_{sij}, \qquad j \neq i \qquad (3)$$

where C_{ij} is the coupling capacitance per unit length between the i th conductor and j th conductor. The coupling capacitances are illustrated in Fig. 1.

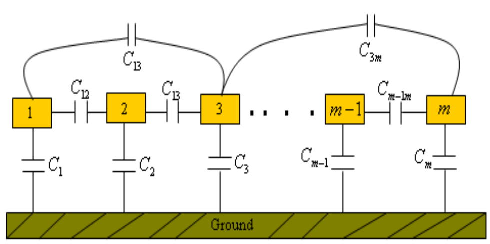

Fig. 1. The per-unit length capacitances of a general m -conductor transmission line.

For m -strip line, the per-unit-length capacitance matrix [C] is given by

$$[C] = \begin{bmatrix} C_{11} & -C_{12} & \cdots & -C_{1m} \\ -C_{21} & C_{22} & \cdots & -C_{2m} \\ \vdots & \vdots & & \vdots \\ -C_{m1} & -C_{m2} & \cdots & C_{mm} \end{bmatrix} \qquad (4)$$

For a triple coupled CPW lines, the capacitance matrix can be defined as:

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} C_{11} & -C_{12} & -C_{13} \\ -C_{12} & C_{22} & -C_{12} \\ -C_{13} & -C_{12} & C_{11} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \qquad (5)$$

In any electromagnetic field analysis, the placement of far-field boundary is an important concern, especially when dealing with open solution regions. It is necessary to take into account that the natural boundary of a line at an infinity and presence of remote objects and their potential influence on the field [8]. In all our simulations, the open models are surrounded by a $W \times H$ shield, where W is the width and H is the thickness.

We illustrate in this article the modeling of multilayer CPW broadside coupled lines balun which is recently developed by the authors. Balun is a device which converts balanced to unbalanced transmission lines that join balanced structures and unbalanced structures [9]. Indeed, multilayer CPW broadside coupled lines balun is widely applied on microwave integrated circuit of wireless communication systems. Therefore, we focus here on the calculation of self and mutual (coupling) capacitances per unit length and determine the quasi-TEM spectral for the potential distribution of the model.

In Fig. 2, we show the cross-section of the developed multilayer CPW broadside coupled lines balun. The geometry of the model has the following parameters values:

ε_r = dielectric constant = 4.4;

w_1 = width of the lower middle conductor = 1.8 mm;

w_2 = width of the upper middle conductor = 1 mm;

w_3 = width of the upper corners conductors = 19.3 mm;

w_4 = width of the lower corners conductors = 18.9 mm;

t = thickness of the conductors = 0.01mm;

h_1 = height of the lower conductors from the ground = 1.6 mm;

h_2 = height of the upper conductors from the ground = 2 mm;

$s_1 = s_2 = 0.2$mm;

The geometry is enclosed by a 40×10 mm shield.

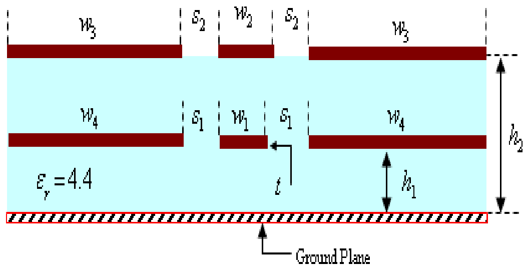

Fig. 2. Cross section of multilayer CPW broadside coupled-line balun.

From the model, we generate the finite element mesh plot as in Figure 3. Table I shows the statistical properties of the model mesh.

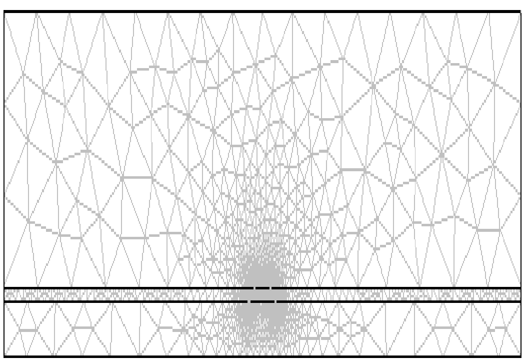

Fig. 3. Mesh plot of multilayer CPW broadside coupled-line balun.

Table I. Mesh statistics of the multilayer CPW broadside coupled-line balun

Items	Value
Number of degrees of freedom	12059
Total number of mesh points	2907
Total number of elements	5388
Triangular elements	5388
Quadrilateral elements	0
Boundary elements	428
Vertex elements	28

Figure 4 shows the 2D surface for electrical potential (V) distribution of the transmission lines, while the contour of electric potential (V) plot of the model is presented in Figure 5.

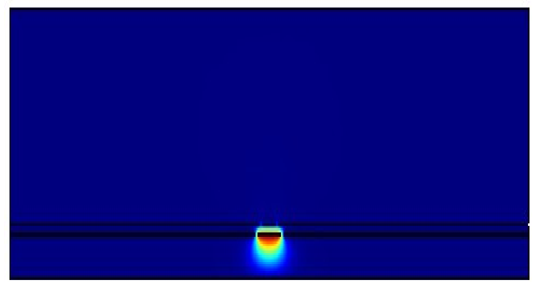

Fig. 4. 2D surface electrical potential distribution of the multilayer CPW broadside coupled-line balun.

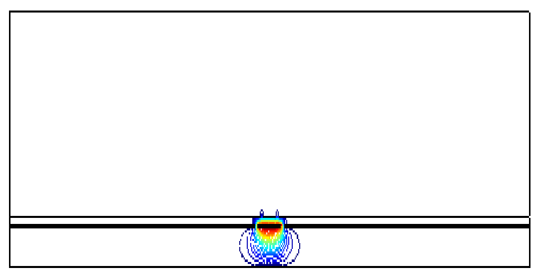

Fig. 5. Contour plot of the multilayer CPW broadside coupled-line balun.

Figure 6 shows the electric potential plot as a function of arc-length of the model. Fig. 7 shows the comparison analysis of potential distribution of the model with and without dielectric substrate. It observed that the peak value of electric potential approximately stays the same as the dielectric is placed in the substrate.

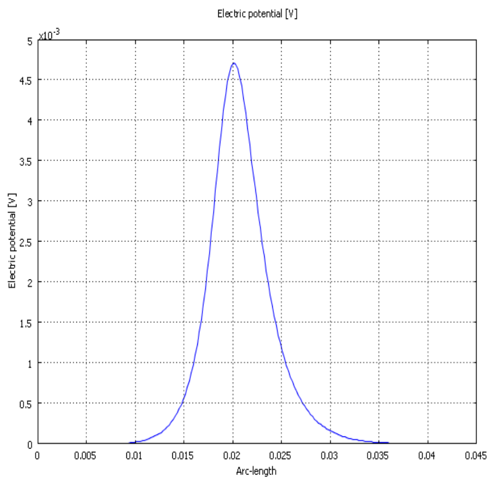

Fig. 6. Potential distribution of multilayer CPW broadside coupled-line balun from (x,y) = (0,0) to (x,y) = (40, 10) mm.

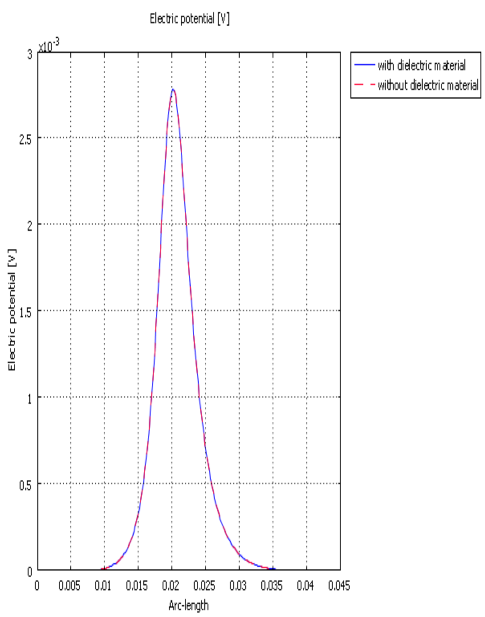

Fig. 7. Comparison analysis of potential distribution of the model with and without dielectric substrate.

The following electrical parameters, capacitance per unit length matrix ($\left[C\right]$ in pF/m) and inductance per unit length ($\left[L\right]$ μ H/m) are found as:

$$\left[C\right] = \begin{bmatrix} 325.9 & -115.5 \\ -115.5 & 159.5 \end{bmatrix} pF/m .$$

The inductance and capacitance per unit length of multiconductor transmission lines are related as follows:

$$\left[L\right] = \mu_o \varepsilon_o \left[C_o\right]^{-1} , \qquad (5)$$

where,

$\left[L\right]$ = Inductance matrix.

$\left[C_o\right]^{-1}$ = the inverse matrix of the capacitance of the multiconductor transmission line when all dielectric constants are set equal to 1.

μ_o = permeability of free space or vacuum.

ε_o = permittivity of free space or vacuum.

$$[L] = \begin{bmatrix} 0.1824 & 0.0944 \\ 0.0944 & 0.2661 \end{bmatrix} \mu H/m .$$

III. CONCLUTIONS

This paper has successfully demonstrated the use of the FEM method to solve open-region electrostatic problems involving 2-D model of multilayer Coplanar Waveguide (CPW) broadside coupled-line balun system. We computed the capacitance per-unit length and inductance per unit length matrices of the model. Also, we identified the quasi-static spectral for the potential distribution of the developed integrated circuit. The results obtained in this research are encouraging and motivating for further study.

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