Analysis of Multiconductor Quasi-TEM Transmission Lines and Multimode waveguides

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Abstract: This paper presents an analysis approach of multicondcutor quasi-TEM lines transmission interconnect in a single dielectric region and multimode waveguides using the finite element method (FEM). We illustrate that FEM is suitable and effective as other methods for modeling of interconnecting lines in high-speed digital circuits. We mainly focus on designing of five-conductor transmission lines interconnect in a single-layered dielectric medium and multimode waveguides. We computed the capacitance, inductance, and impedance matrices, and then we identify the potential distribution of the five-conductor transmission lines interconnect in a single-layered dielectric medium and multimode waveguides. Our method showed very good accuracy in comparison to the other methods.

Keywords: Capacitance matrix, inductance matrix, impedance matrix, multicondcutor transmission lines, multimode waveguides, finite element method

1. Introduction

Today, the designing of fast electronics circuits and systems with increase of the integration density of integrated circuits led to wide use and cautious analysis of multiconductor interconnects. As the transversal size multiple-conductor transmission lines is reduced, adjacent conductors are electromagnetically coupled so that they must be considered as multimode waveguides [1]. Computation of the matrices of capacitances, inductances, and impedances per unit length of multiconductor quasi-TEM transmission lines is important since these elements are essential parameters in designing of package, lossless transmission line system and microwave circuits. Therefore, the improvement of accurate and efficient computational method to analyze the modeling of multiconductor quasi-TEM transmission lines structure becomes an important area of interest.

Previous attempts at the problem include using the analytical modelization of multiconductor quasi-TEM transmission lines [2], studying the method of decoupled the multiconductor transmission line equations by the method of transformation of voltages and currents to mode voltages and currents to obtain their general solution [3], and using a normalization impedance matrix [4]. Other methods include the matrix algorithm [5], integral equation method [6], variational technique [7], conformal mapping method [8], analytical method [9], Fourier transform method [10], and spectral domain method [11].

In this work, we design five-transmission lines interconnect in a single-layered dielectric medium and multimode waveguides using finite element method (FEM) with COMSOL multiphysics package. 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. We specifically calculate the capacitance, inductance, impedance and the potential distribution of the configurations. We compare some of our results of computing the parameters per unit length with those in the other methods.

2. Results and Discussions

The models are designed with finite elements are unbounded (or open), meaning that the electromagnetic fields should extend towards infinity. This is not possible because it would require a very large mesh. The easiest approach is just to extend the simulation domain “far enough” that the influence of the terminating boundary conditions at the far end becomes negligible. In any electromagnetic field analysis, the placement of far-field boundary is an important concern, especially when dealing with the finite element analysis of structures which are open. It is necessary to take into account the natural boundary of a line at infinity and the presence of remote objects and their potential influence on the field shape [14]. In all our simulations, the open multiconductor structure is surrounded by a W X H shield, where W is the width and H is the thickness.

The models are designed in using electrostatic environment in order to compare our results with 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.

In this paper, we consider two different models. Case A investigates the designing of five-transmission lines interconnect in single-layered dielectric medium. For case B, we illustrate the modeling of symmetrical coupled-strip lines for multimode waveguides. The results from both models are compared with other methods and found to be close.

2.1 Modeling of Five-conductor lines interconnect in a single-layered dielectric medium

In Figure 1, we show the cross section for five-conductor transmission lines and its parameters.

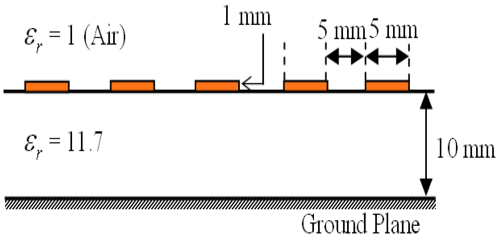

Figure 1. Cross-section of five-conductor transmission lines.

For the modeling, the geometry was enclosed by a 100 X 30 mm shield. Figure 2 shows the finite element mesh which consists of 1400 elements with number of degrees of freedom solved for 15964 in a solution time 2.516 seconds. Figure 3 shows the surface potential distribution of the transmission lines. Counter and streamline plots were presented in Figures 4 and 5 respectively.

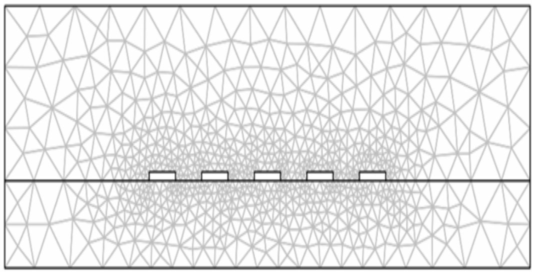

Figure 2. Mesh of five-conductor transmission lines.

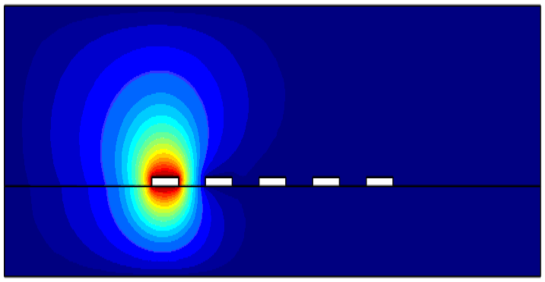

Figure 3. 2D surface potential distribution of five-conductor transmission lines.

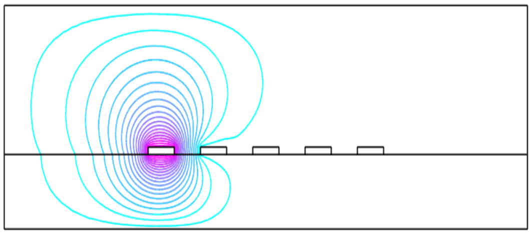

Figure 4. Contour plot of five-conductor transmission lines.

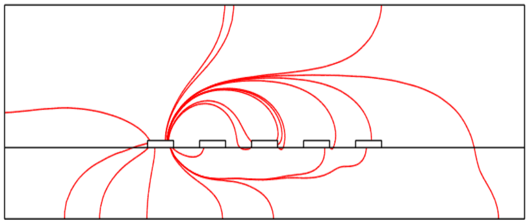

Figure 5. Streamline plot of five-conductor transmission lines.

From our model, Figure 6 shows the potential distribution of the five-conductor transmission lines from (x,y) = (0,0) to (x,y) = (100,30) mm, using port 1 as input.

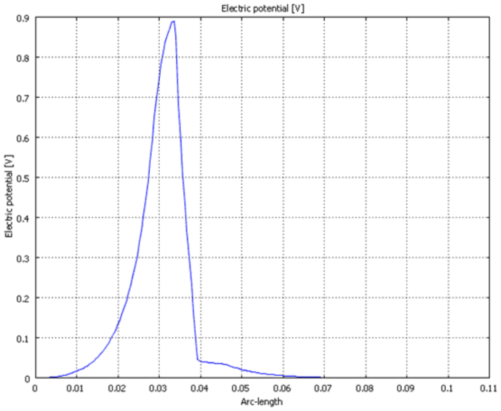

Figure 6. Potential distribution of five-conductor transmission lines from (x,y) = (0,0) to (x,y) = (100,30) mm, using port 1 as input.

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

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

where,

$[L]$ = Inductance matrix.

$[C_o]^{-1}$ = 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.

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

$$[Z] = \sqrt{\frac{[L]}{[C]}} \qquad (2).$$

The following electrical parameters (capacitance per unit length matrix ($[C]$ in pF/m), inductance per unit length ($[L]$ in nH/m), and diagonal matched impedances ($[Z_{dm}]$ in Ω) are found by Matrix Algorithm method [5]:

$$[C] = \begin{bmatrix} 140.136 & -30.789 & -1.907 & -0.382 & -0.195 \\ -30.789 & 153.673 & -30.514 & -1.858 & -0.382 \\ -1.907 & -30.514 & 153.693 & -30.514 & -1.907 \\ -0.382 & -1.858 & -30.514 & 153.673 & -30.789 \\ -0.195 & -0.382 & -1.907 & -0.789 & 140.136 \end{bmatrix}$$

$$[L] = \begin{bmatrix} 497.841 & 164.707 & 76.964 & 41.775 & 25.539 \\ 164.707 & 490.660 & 162.252 & 76.043 & 41.775 \\ 76.964 & 162.252 & 489.489 & 162.252 & 76.964 \\ 41.775 & 76.043 & 162.252 & 490.660 & 164.707 \\ 25.539 & 41.775 & 76.964 & 164.707 & 497.841 \end{bmatrix}$$

$$[Z_{dm}] = \begin{bmatrix} 58.33 & & & & \\ & 54.47 & & & \\ & & 54.25 & & \\ & & & 54.47 & \\ & & & & 58.33 \end{bmatrix}$$

The following results are obtained from our method:

$$[C]=\begin{bmatrix} 163.238 & -35.227 & -1.701 & -0.143 & -0.187 \\ -35.227 & 172.299 & -34.846 & -1.665 & -0.144 \\ -1.701 & -34.846 & 172.347 & -34.816 & -1.706 \\ -0.143 & -1.665 & -34.816 & 172.354 & -35.391 \\ -0.187 & -0.144 & -1.706 & -35.391 & 163.814 \end{bmatrix}$$

By using equation 1, we obtain $[L]$,

$$[L]=\begin{bmatrix} 455.133 & 135.824 & 48.533 & 17.101 & 6.743 \\ 135.819 & 450.868 & 133.718 & 47.907 & 18.381 \\ 50.542 & 139.384 & 449.956 & 133.762 & 49.265 \\ 24.609 & 69.069 & 139.478 & 451.242 & 137.337 \\ 8.953 & 24.611 & 50.581 & 135.965 & 455.414 \end{bmatrix}$$

By using equation 1, we obtain $[Z_{dm}]$,

$$[Z_{dm}]=\begin{bmatrix} 55.29 & & & & \\ & 54.62 & & & \\ & & 54.93 & & \\ & & & 54.60 & \\ & & & & 55.14 \end{bmatrix}$$

The above results shows the finite element results for the electrical parameter of the five-conductor transmission lines interconnect in single-layered dielectric medium using FEM with COMSOL.

2.2 Modeling of Symmetrical Coupled-strip lines for multimode waveguides

In this section, we illustrate the modeling of the symmetrical coupled-strip lines for multimode waveguides. We focus on the calculation of capacitance per unit length, the capacitance with homogenous dielectric layer, inductance, and the characteristic impedance. In Fig. 7, we show the cross-section of symmetrical coupled-strip lines for multimode waveguides with the following parameters:

$w_1 =$ width of strip 1

$w_2 =$ width of strip 2

$s =$ distance between the strip 1 and strip 2

$t =$ thickness of the strips

$h_1 =$ height of the strips from the ground

$w_1 = w_2 = s = 500\mu m$, $t = 17\mu\text{m}$

$h_1 = 635\text{m}$.

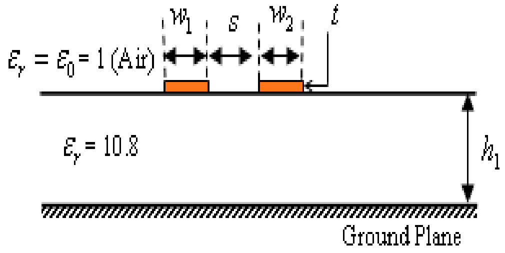

Figure 7. Cross-section of symmetrical strips coupled-strip lines for multimode waveguides.

For the modeling, the geometry was enclosed by a 7500 X 3175 μm shield. Figure 8 shows the finite element mesh which consists of 2446 elements with number of degrees of freedom solved for 27539 in a solution time 4.843 seconds. While, Figure 9 shows the 2D surface potential distribution of the transmission lines. Counter and streamline plots were presented in Figures 10 and 11 respectively.

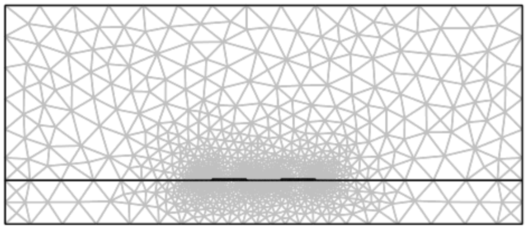

Figure 8. Mesh of symmetrical strips as multimode waveguides.

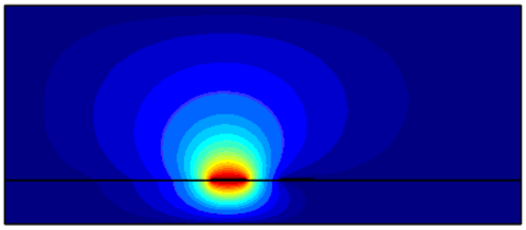

Figure 9. 2D surface potential distribution of symmetrical coupled-strip lines for multimode waveguides.

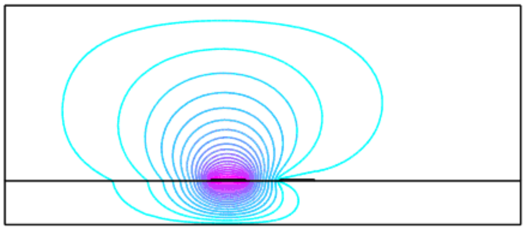

Figure 10. Contour plot of symmetrical coupled-strip lines for multimode waveguides.

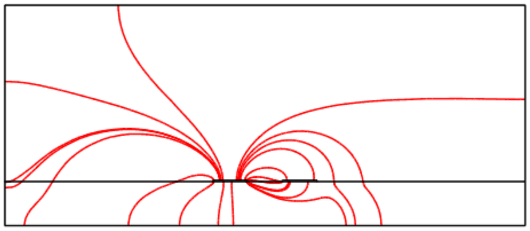

Figure 11. Streamline plot of symmetrical coupled-strip lines for multimode waveguides.

From our model, Figure 12 shows the potential distribution of the five-conductor transmission lines from (x,y) = (0,0) to (x,y) = (7500,3175) μm, using port 1 as input.

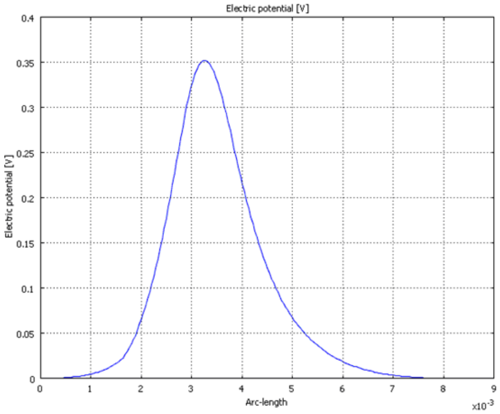

Figure 12. Potential distribution of symmetrical coupled-strip lines for multimode waveguides from (x,y) = (0,0) to (x,y) = (7500,3175) μm, using port 1 as input.

The following electrical parameters (capacitance per unit length matrix ($[C]$ in pF/m), inductance per unit length ($[L]$ in nH/m), and characteristic impedances matrix ($[Z]$ in Ω) are found as :

$$C = \begin{bmatrix} 173.6261 & -21.38597 \\ -21.38597 & 173.6261 \end{bmatrix}$$

$$[L] = \begin{bmatrix} 437.1 & 92.2 \\ 92.2 & 437.1 \end{bmatrix}$$

$$[Z] = \begin{bmatrix} 51.2149 & 29.2288 \\ 29.2288 & 51.2149 \end{bmatrix}$$

We provided the results of FEM in two-dimensional compared with some other methods for the designing of five-transmission lines interconnect in a single-layered dielectric medium and multimode waveguides. The results of capacitance matrices for self and mutual capacitances, inductance matrices, and impedance matrices which are useful for the analysis of crosstalk between high-speed signal traces on the printed circuit board are compared with other published data for the validity of the proposed method.

3. Conclusions

In this paper we have presented the modeling in 2D of designing of five-conductor lines interconnect in a single-layered dielectric medium and symmetrical coupled-strip lines for multimode waveguides. We have shown that FEM is suitable and effective as other methods for modeling lines interconnect in single-layered dielectric medium and multimode waveguides. We have shown that FEM is suitable and effective as other methods for modeling multiconductor transmission lines in VLSI circuits. Some of the results obtained using FEM with COMSOL multiphysics for the capacitance-per-unit length, inductance, impedances agree well with those found in the experimental and other methods. The results obtained in this research are encouraging and motivating for further study.

4. References

1. C. Seguinot, E. Paleczny, F. Huret, J. F. Legier, and P. Kennis, “Experimental determination of the characteristic impedance matrix of multiconductor quasi-TEM lines,” *Microwave Theory and Optical Technology Letters*, vol. 22, no. 6, pp. 429-431, Sep. 1999.
2. P. Pannier, E. Paleczny, C. Seguinot, F. Huret, P. Kennis, “analytical and full-wave characterization of multimode waveguide discontinuities,” 27th European Microwave Conference, vol. 1, pp. 485 – 489, 1997.
3. C. R. Paul, “Decoupling the multiconductor transmission line equations,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 44, no. 8, pp. 1429-1440, Aug. 1996.
4. C. Seguinot, E. Paleczny, P. Kennis, F. Huret, and J. F. Legier, “Reciprocity normalized matrix representation of quasi-TEM multimode multiports,” *Microwave Theory and Optical Technology Letters*, vol. 20, no. 3, pp. 214-218, Feb. 1999.
5. Y. You, O. A. Palusinski, and F. Szidarovszky, “New matrix algorithm for calculating diagonally matched impedance of packaging interconnecting lines,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 6, pp. 798-801, Jun. 1999.
6. D. W. Kammler, ”Calculation of characteristic admittances and coupling coefficients for strip transmission lines”, *IEEE Transmissions on Microwave Theory and Techniques*, Vol. 16, No. 11, November 1968, pp. 925-937.
7. F. Medina and M. Horno, ” Capacitance and inductance matrices for multistrip structures in multilayered anisotropic”, *IEEE Transmissions on Microwave Theory and Techniques*, Vol. 35, No. 11, November 1987, pp. 1002-1008.
8. D. Homentcovschi, A. Manolescu, A. M. Manolescu and L. Kreindler**,** “An analytical solution for the coupled stripline-like microstrip line problem”, *IEEE Transmissions on Microwave Theory and Techniques*, Vol. 36, No. 6, June 1988, pp. 1002-1007.
9. M. K. Amirhosseini and A. Cheldavi, ”Time domain analysis of circulant symmetric coupled transmission lines”, *IEE Proceedings of Microwaves, Antennas and Propagation*, Vol. 150, No.5, October 2003, pp. 325-31.
10. S. Voranantakul, J. L. Prince and P. Hsu, ”Crosstalk analysis for high-speed pulse propagation in lossy electrical interconnections”, *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, Vol. 16, No. 1, February 1993, pp. 127-136.
11. R. Schwindt and C. Nguyen, “Spectral domain analysis of three symmetric coupled lines and application to a new bandpass filter”, *IEEE Transmissions on Microwave Theory and Techniques*, Vol. 42, No. 7, July 1994, pp. 1183-1189.
12. Y. R. Crutzen, G. Molinari, and G. Rubinacci (eds.), *Industrial Application of Electromagnetic Computer Codes.* Norwell, MA: Kluwer Academic Publishers, 1990, p. 5.