Quasi-static Analysis on the Effect of Metal Penetrating Depth into the Substrate in Microstriplines

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Abstract: Finite thickness of planar transmission lines plays an essential role in the propagation characteristics and the electric field distributions in the structures of planar transmission lines for monolithic microwave integrated circuits. In this paper, we illustrate fast and accurate modeling applying finite element method. We design a shielded microstripline with finite metallization thickness not penetrating and penetrating into isotropic substrate. Also, we investigate coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes. We specifically determine the characteristic impedances of the shielded microstripline and the capacitance per unit length of the coupled lines. Comparison of our results with other available methods is demonstrated with excellent agreements.

Keywords: Finite element method, planar transmission lines, capacitance per unit length, characteristic impedances, metallization thickness, isotropic substrate.

1. Introduction

The effect of metallization thickness on planar transmission line plays an essential role in microwave integrated circuits and thin film technology, especially in the propagation characterization and the electric field distribution in the structures. Therefore, the analysis of finite metallization thickness of planar transmission line is important for integrated circuit design. The assumption of infinitely thin metallization thickness becomes insufficient for designers, because the typical metallization thickness is ranged from 2 μm to 3 μm, which is similar to the dimensions of the stripline widths in MMICs and optical integrated circuits [1-4].

In the past, planar transmission lines with finite metallization thickness have been thoroughly investigated by many authors and many methods such as finite difference method [5], boundary element method [6], variational technique [7], step current density approximation [8], method of lines [9], mode matching method [10-12], point-matching method [13-14], conformal mapping techniques [15], mixed spectral-space domain method [16], vertical directional mode-matching method [17], and Green's function method [18].

The objective of this paper is to consider the planar transmission lines with finite thickness not penetrating and penetrating into isotropic substrate to present computer-aided analysis using finite element method (FEM) with COMSOL that allows simple and accurate computation of its design parameters.

We illustrate that our method using FEM is suitable, accurate and effective as other methods for modeling of quasi-static single shielded microstripline with finite metallization thickness not penetrating and penetrating into isotropic substrate. Also, it is accurate and effective for designing coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes.

In this work, we focus on the calculation of the characteristic impedances and the capacitance per unit length matrix of the finite thickness of planar transmission lines, and then compare the results of our modeling with some previous works.

2. Discussion and Results

The models are designed in two-dimensional (2D) 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. We find the capacitance per unit length of the line from the model's design results, and then we use the results of our computation to find the characteristic impedance.

The characteristic impedance of such a lossless line is given by

$$Z_c = \frac{1}{c\sqrt{CC_o}} \qquad (1)$$

where
Z_c = characteristic impedance of the line
C_o = capacitance per unit length of the line when the substrate is replaced with air
C = capacitance per unit length of the line when the substrate is in place
c = 3 x 10^8 m/s (the speed of light in vacuum)

We use FEM in our computations because it is suitable for the computation of electric and electromagnetic fields in strongly inhomogeneous media and it has high computation accuracy and fast computation speed. These capabilities make FEM effective as other methods in modeling planar transmission lines with finite thickness.

In the following subsections, we demonstrate our design on modeling of quasi-static single shielded microstripline with finite metallization thickness not penetrating and penetrating into isotropic substrate, and then design coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes.

2.1 Single Shielded Microstripline with Finite Metallization Thickness Penetrating and Not Penetrating into Isotropic Substrate

In this section, we illustrate the modeling of shielded single microstripline with finite metallization thickness penetrating and not penetrating into isotropic substrate by focusing only on the calculation of characteristic impedance (Z_c). Figure 1 shows the geometry of the model with the following parameters:

ε_0 = permittivity of free space $= \frac{1}{36\pi}\times 10^{-9} = 8.854\times 10^{-12}$ F/m

ε_r = dielectric constant = 4.7

L = width of the grounded shield = 1mm (homogeneous case) and 295mil (inhomogeneous case)

W = width of the microstrip line = 0.2mm (homogeneous case) and 15mil (inhomogeneous case)
L_1 = height of the free space from the dielectric material = 0.55mm (homogeneous case) and 140mil (inhomogeneous case)
L_2 = height of the dielectric material from the ground = 0.45mm (homogeneous case) and 14mil (inhomogeneous case)
t_1 = thickness of the microstrip not penetrating into isotropic substrate = 0.1mm (homogeneous case), and 2.8mil (inhomogeneous case)
t_2 = thickness of the microstrip penetrating into isotropic substrate = 0, 0.1mm, 0.2mm (homogeneous case), and 2.8mil (inhomogeneous case).

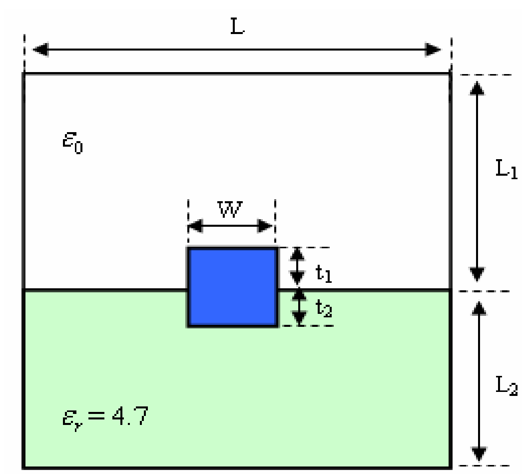

Figure 1. Cross-section of a shielded microstripline with finite metallization thickness penetrating into isotropic substrate.

Figure 2 shows the potential distribution at y = 0.45 mm with maximum potential at 0.4 mm for homogenous case at $t_1 = t_2 = 0.1$ mm. The potential has a negative slope from 0.4 to 0.6mm.

Figure 3 shows the potential distribution at y = 0.45 mm with maximum potential between 0.4 mm and 0.6 mm for homogenous case at $t_1 = t_2 =$ 0.1 mm. The potential has a constant slope from 0.4 to 0.6mm. Figure 4 shows the potential distribution of a shielded microstripline with finite metallization thickness penetrating into isotropic substrate from (x,y) = (0,0) to (x,y) = (295, 154)mil for inhomogeneous case at t_1 = 2.8mil and t_2 = 0 mil. Figure 5 shows the potential distribution of shielded a microstripline with finite metallization thickness penetrating into isotropic substrate from (x,y) = (0,0) to (x,y) = (295, 154)mil for inhomogeneous case at t_1 = t_2 = 2.8mil

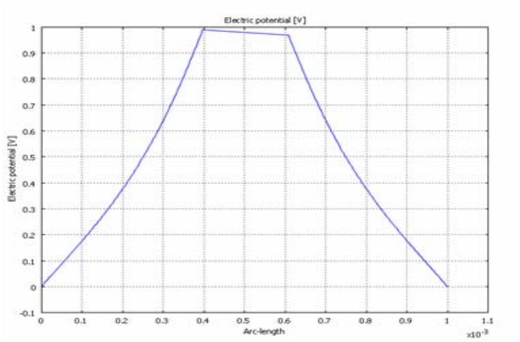

Figure 2. Potential distribution of a shielded microstripline with finite metallization thickness penetrating into isotropic substrate at line y = 0.45 mm for homogenous case at t_1 = t_2 = 0.1 mm.

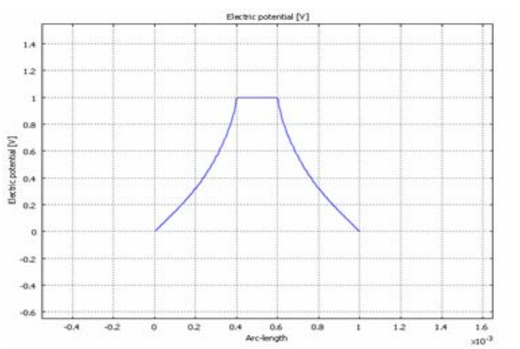

Figure 3. Potential distribution of a shielded microstripline with finite metallization thickness penetrating into isotropic substrate at line y = 0.45 mm for homogenous case at t_1 = 0.1 and t_2 = 0 mm.

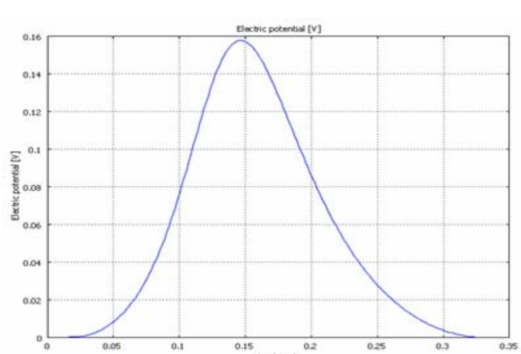

Figure 4. Potential distribution of a shielded microstripline with finite metallization thickness not penetrating into isotropic substrate from (x,y) = (0,0) to (x,y) = (295, 154)mil for inhomogeneous case at t_1 = 2.8mil and t_2 = 0 mil.

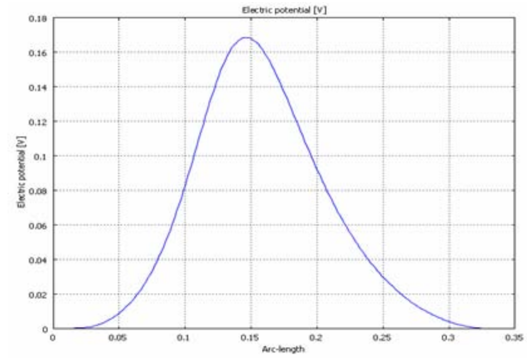

Figure 5. Potential distribution of a shielded microstripline with finite metallization thickness penetrating into isotropic substrate from (x,y) = (0,0) to (x,y) = (295, 154)mil for inhomogeneous case at t_1 = t_2 = 2.8mil.

Table 1 shows the FEM results for the characteristic impedance of the structure compared with other methods when the finite metallization thickness not penetrating into isotropic substrate. They are agreeable with those calculated by other methods. Also, we computed the case for the finite metallization thickness penetrating into isotropic substrate.

Table 1: Calculated values characteristic impedance Z_c (in Ω) for homogenous shielded single microstripline with finite metallization thickness penetrating and not penetrating into isotropic substrate

Characteristic Impedance for L_1 = 0.55mm, L_2 = 0.45mm, L = 1mm, W = 0.2mm	Ref. [9]	Ref. [6]	Ref. [14]	Ref. [17]	Our Work
Z_c (in Ω) at t_1 = 0.1 mm and t_2= 0	108.53	108.96	108.07	109.32	108.82
Z_c (in Ω) at t_1 = t_2= 0.1 mm	-	-	-	-	90.41
Z_c (in Ω) at t_1 = 0.1 mm and t_2= 0.2mm	-	-	-	-	75.27

Table 2 shows the FEM results for the characteristic impedance of the inhomogeneous structure compared with other methods when the finite metallization thickness not penetrating into isotropic substrate. They are agreeable with those calculated by other methods. Also, we computed the case for the finite metallization thickness penetrating into isotropic substrate.

Table 2: Calculated values characteristic impedance Z_c (in Ω) for the inhomogeneous shielded single microstripline with finite metallization thickness penetrating and not penetrating into isotropic substrate

Characteristic Impedance for L_1 = 140mil, L_2 = 14mil, L = 295mil, W = 15mil	Ref. [16]	Ref. [6]	Ref. [18]	Ref. [17]	Our Work
Z_c (in Ω) at t_1 = 2.8 mil and t_2= 0	61.73	61.60	61.80	61.61	61.50
Z_c (in Ω) at $t_1 = t_2$ = 2.8 mil	-	-	-	-	49.49

Based on the tables, we observed that the penetrating depth of the microstripline affects the propagation characteristic of the shielded microstripline, because as the metal penetrated with depth t_2 increases, the characteristic impedances of the shielded microstripline reduce.

2.2 Coupled Lines with Asymmetrical Metallization Thickness Not Penetrating and Penetrating into Isotropic Substrate between Two Ground Planes

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 infinity and the presence of remote objects and their potential influence on the field shape [13]. In all our simulations, the coplanar structures is surrounded by a w X h shield, where w is the width and h is the thickness of the shield.

In this section, we demonstrate the modeling of coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes by focusing only on the calculation of the capacitance per unit length matrix. Figure 6 shows the geometry of the model with the following values:

ε_0 = permittivity of free space $= \dfrac{1}{36\pi}\times 10^{-9} = 8.854\times 10^{-12}$ F/m

ε_r = dielectric constant = 2.0

L = width of the grounded shield = 40mm

W_1 = width of the microstrip line 1 = 3mm

W_2 = width of the microstrip line 2 = 3mm

G = distance between the two microstrip lines = 2mm

L_1 = height of the free space from the dielectric material = 2.7mm

L_2 = height of the dielectric material from the ground = 1mm

t_1 = thickness of the microstrip 1 not penetrating into isotropic substrate = 1mm and 0.5mm

t_2 = thickness of the microstrip 1 penetrating into isotropic substrate = 0mm and 0.5mm

t_3 = thickness of the microstrip 2 not penetrating into isotropic substrate = 1mm and 0.5mm

t_4 = thickness of the microstrip 2 penetrating into isotropic substrate = 0mm and 0.5mm.

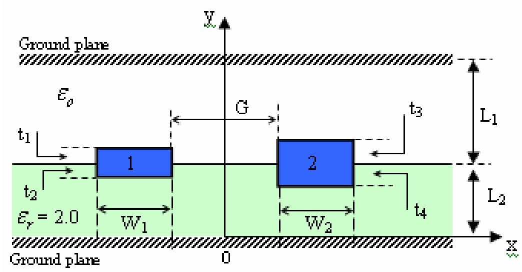

Figure 6. Cross-section of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes.

Figure 7 shows the potential distributions of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes at line y = 1 mm when $t_1 = t_3$ =1mm, $t_2 = t_4 = 0$. Figure 8 shows the potential distributions of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes from (x,y) = (0, 3.7mm) to (x,y) = (0, 40mm) when $t_1 = t_3 = t_2 = t_4$ = 0.5mm.

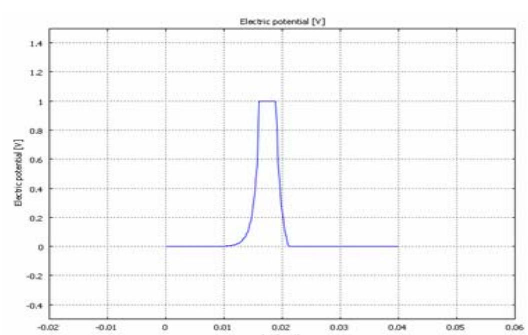

Figure 7. Potential distributions of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes at line y = 1 mm when $t_1 = t_3$ =1mm, $t_2 = t_4$ = 0.

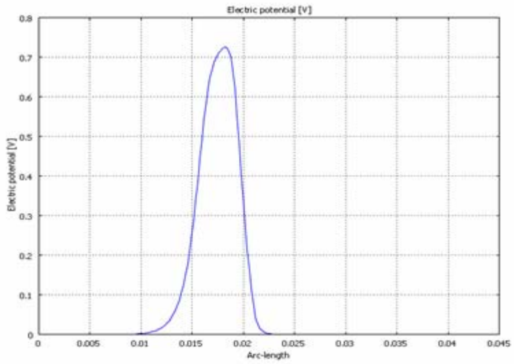

Figure 8. Potential distributions of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes from (x,y) = (0, 3.7mm) to (x,y) = (0, 40mm) when $t_1 = t_3 = t_2 = t_4 = 0.5$mm..

Table 3 shows the FEM results for the capacitance matrix of the structure of the model of coupled lines with asymmetrical metallization thickness penetrating into isotropic substrate between two ground planes. The results are compared with the pervious work and found to be in good agreement.

Table 3: Calculated values of capacitance matrix (in pF/m) coefficients for the coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes

Capacitance matrix ($C_{ij} = C_{ji}$) and ($C_{ii} = C_{jj}$)	Ref. [16]	Ref. [19]	Ref. [14]	Ref. [10]	Ref. [12]	Our Work
$C_{11} = C_{22}$ at $t_1 = t3 = 1$mm, $t_2 = t_4 = 0$	108.1	109.1	108.8	107.3	108.7	107.04
$C_{12} = C_{21}$ at $t_1 = t_3 = 1$mm, $t_2 = t_4 = 0$	-4.571	-4.712	-4.683	-4.514	-4.615	-4.666
$C_{11} = C_{22}$ at $t_1 = t_3 = t_2 = t_4 = 0.5$mm	-	-	-	-	-	173.583
$C_{12} = C_{21}$ at $t_1 = t_3 = t_2 = t_4 = 0.5$mm	-	-	-	-	-	-4.966

3. Conclusions

In this paper, we have presented modeling of shielded single microstripline with finite metallization thickness not penetrating and penetrating into isotropic substrate. Also, we investigate coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes. We computed the characteristic impedance of shielded single microstripline with finite metallization thickness not penetrating and penetrating into isotropic substrate and the capacitance matrix of the coupled lines with asymmetrical metallization thickness not penetrating and penetrating into isotropic substrate between two ground planes. Close agreement with published results has been obtained.

4. References

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