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Finite Element Approach of Shielded, Suspended and Inverted Microstrip Lines

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Abstract

In this paper, we present finite element method (FEM) to investigate the electromagnetic analysis of two-dimensional (2D) shielded, suspended and inverted microstrip lines for microwave applications. In the proposed method, we specifically determine the values of capacitance per unit length, inductance per unit length, and characteristic impedance of the microstrip lines. Extensive simulation results are presented and some comparative results are given with other methods and found them to be in excellent agreement. We extend the analysis by designing our new model of shielded, inverted microstrip lines and compared it with shielded, suspended microstrip lines; we found them to be very close. Also, we determine the quasi-TEM spectral for the potential distribution of these microstrip lines.

Keywords: Finite element method, suspended microstrip line, inverted microstrip line, electromagnetic parameters

1. Introduction

Electromagnetic simulation and modeling of suspended-substrate microstrip lines have an important role in designing microwave and millimeter-wave integrated circuits. Suspended-substrate microstrip lines are sometimes manufactured and placed in a shield to reduce performance degradation from external influences. During recent years, simulation of high performance systems such as in microwave integrated circuit packaging design based on numerical analysis has been essential in the electromagnetic field technology. Advances in integrated circuit technology have caused renewed interest in the computation of capacitance, inductance, or characteristic impedance of microstrip lines. Therefore, their computation has become important for designers.

Several methods used for analyzing transmission lines structure include the least-square curve-fitting technique [1, 2], the conformal mapping approach [3], the variational method [4], the HFSS simulator [5], the spectral domain analysis (SDA) [6], and the finite-difference time-domain (FDTD) method [7].

In this work, we propose finite-element method (FEM) in the quasi-TEM mode analysis of the microstrip transmission lines structure of shielded, suspended and inverted microstrip lines, in order to show that FEM is especially suitable for the computation of electromagnetic fields in strongly inhomogeneous media. Also, it has high computation accuracy and fast computation speed. Indeed, this article opens a new area of research which is based in our new design of shielded, inverted microstrip line. Although, we use FEM to compute the capacitance per unit length, inductance per unit length, and characteristic impedance of shielded, suspended and inverted microstrip lines, and then compare some of the results of our modeling with the previous methods, then identify the potential distribution spectra of the integrated circuits.

2. Theory for the Problem Formulation of Microstrip lines in Dielectric Media

Suspended-substrate microstrip lines have been extensively used in microwave and millimeter-wave integrated circuits, due to their attractive features of having low attenuation and large tolerance of fabrication, weak dispersion, small effective dielectric constant, low

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propagation loss, and low insertion loss. The microwave active and passive circuits use it as millimeter-wave mixers, oscillators, frequency multipliers, filters, directional couplers, power dividers, transistor amplifiers and so on. Due to the air gap between the substrate and the ground plane of shielded suspended-substrate microstrip lines, it decreases the dispersion of the line parameters and reduces losses in the line.

The inductance per unit length L and capacitance per unit length C_o of a single-strip microstrip line are related as

$$L = \frac{\mu_o \varepsilon_o}{C_o} \tag{1}$$

where

$\varepsilon_o =$ permittivity of free space or vacuum ($\frac{10^{-9}}{36\pi}$).

$\mu_o =$ permeability of free space or vacuum (12.6 X 10^{-7}).

C_o = capacitance per unit length of the microstrip line while the relative permittivity is equal to 1.

The characteristic impedance and the capacitance are related as

$$Z_o = \sqrt{\frac{\mu_o \varepsilon_o}{C_o C}} = \frac{1}{u\sqrt{C_o C}} \tag{2}$$

where

Z_o = characteristic impedance of the microstip line.

C = capacitance of the microstrip line

u = 3 X 10^8 m/s (the speed of light in vacuum).

3. Results and Discussion

In this paper, we consider two different models. First case, investigates the modeling of shielded suspended microstrip line. We identify the quasi-TEM spectral for the potential distribution of the designed model and its mesh. Also, we computed the values of capacitances and inductance at different parameters and at different dielectric constants, and then we find the characteristic impedances of the model and compare them with the other methods. Indeed, we compare the values of characteristic impedances at different dielectric constants for different structure parameters. For second case, we illustrate the modeling of our new shielded inverted microstrip line. We identify the quasi-TEM spectral for the potential distribution of the new designed model and its mesh. In addition, we computed the values of capacitances, inductance, and characteristic impedances at different structure parameters and at different dielectric constants, and then compare these values with shielded suspended microstrip line.

3.1. Shielded suspended microstrip line

In this section, we illustrate the designing and modeling of the shielded suspended microstrip line by focusing on the potential distribution and meshing. Also, we compute the capacitance per unit length, inductance per unit length, and characteristic impedance of the microstrip line. In Figure 1, we show the cross section for shielded suspended microstrip line with the following parameters:

ε_r = dielectric constant = 2.22, 9.8, and 12.9

w = width of the strip = 0.1 h, h, and 5 h

t = thickness of the strip = 0.01mil.

h = thickness of the dielectric material = 25mil.

b_1 = height of the dielectric material from the ground = 475 mil.

b_2 = distance of the dielectric material from the top= 500 mil.
b = height of the shield = 1000 mil.
a = width of the shield = 1000 mil.

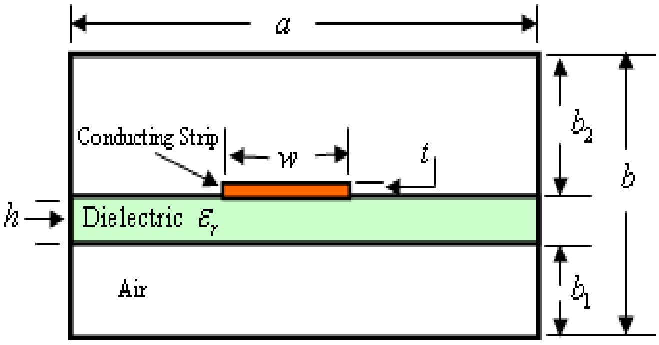

Figure 1. Cross-section of shielded suspended microstrip line

Table 1. Mesh statistics of the shielded suspended microstrip

Items	Value
Number of degrees of freedom	24632
Total Number of mesh points	6115
Total Number of elements	12058
Triangular elements	12058
Quadrilateral	0
Boundary elements	583
Vertex elements	12

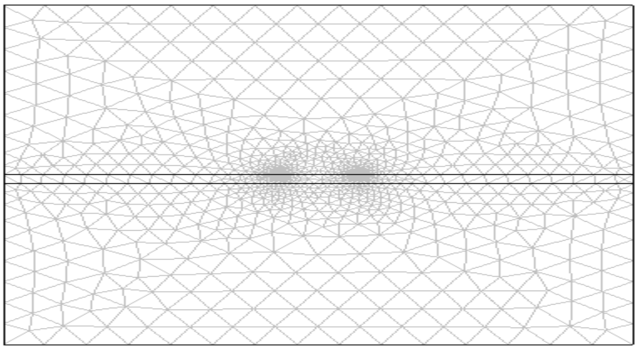

Figure 2. Mesh plot of shielded suspended microstrip line with $w = 5h$

Table 1. Mesh statistics of the shielded suspended microstrip

Items	Value
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Vertex elements	12

From the model, we generate the finite element mesh plot as in Fig. 2. Table 1 shows the statistical properties of the mesh. While, Fig. 3 shows the 2D surface potential distribution for

$w=5h$; although the contour plot is presented in Fig. 4. Figure 5 presents the electric potential plot as a function of arc-length. In addition, Fig. 6 shows the comparison analysis of potential distribution of the model with and without dielectric substrate. It observed that the peak value of electric potential is increased as the dielectric is placed in the substrate.

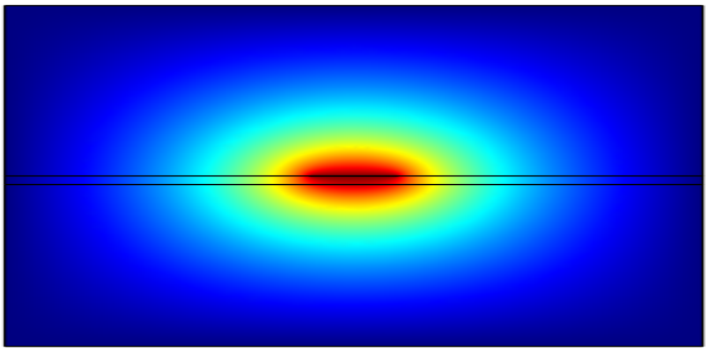

Figure 3. 2D surface potential distribution of shielded suspended microstrip line with $w=5h$

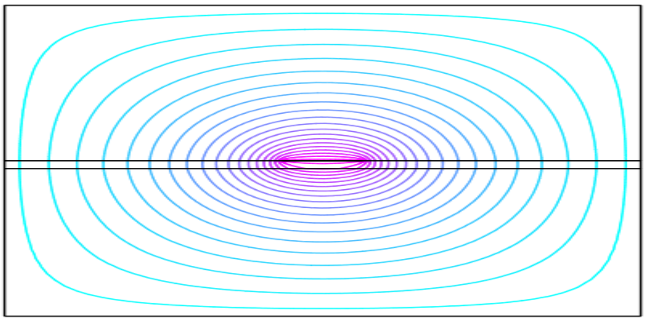

Figure 4. Contour plot of shielded suspended microstrip line with $w=5h$

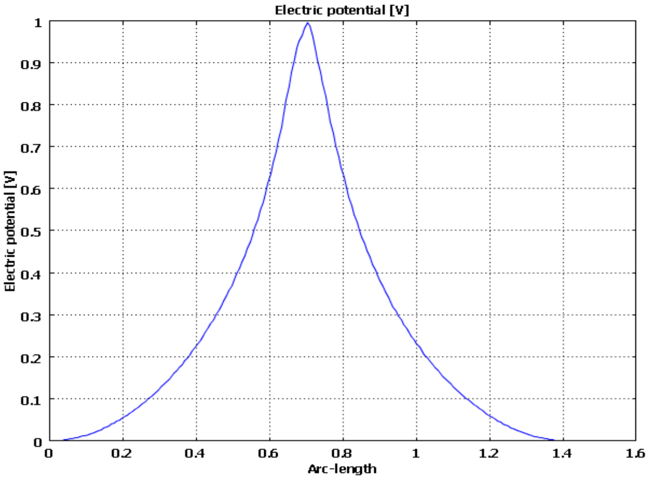

Figure 5. Potential distribution of shielded suspended microstrip line with $w=5h$ from $(x,y)=(0,0)$ to $(x,y)=(1,1)$ mil

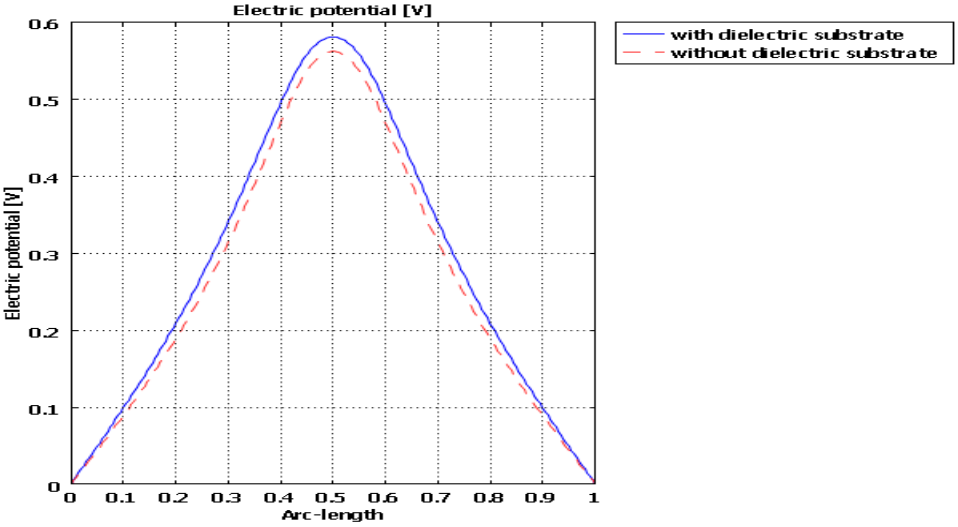

Figure 6. Potential distribution of shielded suspended microstrip line with $w = 5h$ at y = 0.6 mil

The simulation was done twice–once to calculate C when ε_r = 2.22, 9.8, and 12.9 and the other to calculate C_o when ε_r = 1.0. We need C_o to calculate the inductance L and the impedance Z_o according to eqs. (1) and (2) respectively. Tables 2, 3 and 4 show the finite element results for the capacitance per unit length C and the inductance per unit length L of shielded suspended microstrip line when ε_r = 2.22, 9.8, and 12.9 respectively.

Table 2. Capacitance and inductance of the shielded suspended microstrip line when $\varepsilon_r = 2.22$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)
0.1	8.24	10.98	1.35
1.0	12.48	15.32	0.89
5.0	19.53	22.12	0.57

Table 3. Capacitance and inductance of the shielded suspended microstrip line when $\varepsilon_r = 9.8$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)
0.1	8.24	21.30	1.35
1.0	12.48	25.57	0.89
5.0	19.53	32.06	0.57

Table 4. Capacitance and inductance of the shielded suspended microstrip line when $\varepsilon_r = 12.8$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)
0.1	8.24	24.56	1.35
1.0	12.48	28.91	0.89
5.0	19.53	35.52	0.57

The results of characteristic impedance Z_o when ε_r = 2.22 in Table 5 are compared with the work of previous investigations, such as, the Empirical Model (EM), the Variational Method (VM), and the High Frequency Structure Simulation (HFSS) tool. They are in good agreement.

Table 5. Comparison of characteristic impedance (Z_o in Ω) of the shielded suspended microstrip line when $\varepsilon_r = 2.22$

w/h	EM [5]	VM [5]	HFSS [5]	Our work
0.1	329.11	350.98	366.82	350.54
1.0	228.69	242.22	255.46	241.05
5.0	151.16	161.59	165.19	160.38

Table 6 shows the characteristic impedance (Z_o in Ω) of the shielded suspended microstrip line when $\varepsilon_r = 2.22$, $\varepsilon_r = 9.8$ and $\varepsilon_r = 12.9$. It's clear from the table that the characteristic impedance Z_o of the shielded suspended microstrip line becomes lesser when the width of the microstrip increased and when the dielectric constant ε_r increased.

Table 6. Characteristic impedance (Z_o in Ω) of the shielded suspended microstrip line when $\varepsilon_r = 2.22$, $\varepsilon_r = 9.8$ and $\varepsilon_r = 12.8$

w/h	$\varepsilon_r = 2.22$	$\varepsilon_r = 9.8$	$\varepsilon_r = 12.8$
0.1	350.54	251.56	234.27
1.0	241.05	186.60	175.52
5.0	160.38	133.23	126.56

3.2. Shielded inverted microstrip line

No closed form expression or model for shielded inverted microstrip line has been reported yet. Therefore, we developed our new model for the shielded inverted microstrip line using FEM. In Figure 7 we show the cross section for the shielded inverted microstrip line with the following parameters:

ε_r = dielectric constant = 2.22, 9.8, and 12.9
w = width of the strip = 0.1 h , h , and 5 h
t = thickness of the strip = 0.01mil.
h = thickness of the dielectric material = 25mil
b_1 = distance of the dielectric material from the ground = 475 mil.
b_2 = height of the dielectric material from the top= 500mil.
b = height of the shield = 1000 mil.
a = width of the shield = 1000 mil.

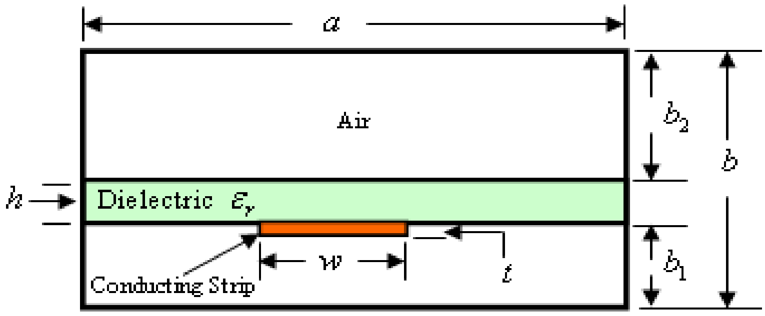

Figure 7. Cross-section of shielded inverted microstrip line

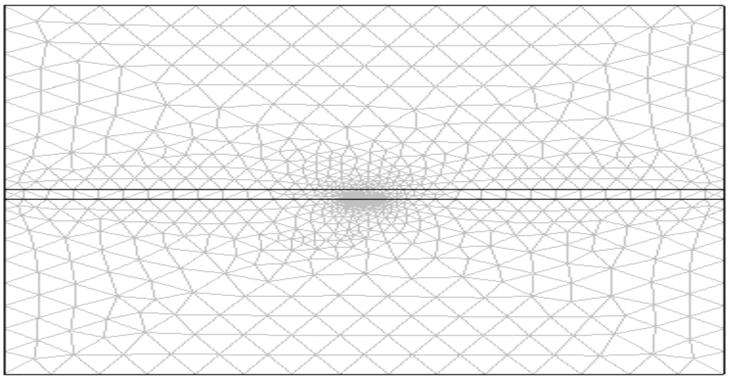

Figure 8. Mesh plot of shielded inverted microstrip line with $w = h$

Table 7. Mesh statistics of the shielded inverted microstrip line

Items	Value
Number of degrees of freedom	130905
Total Number of mesh points	30923
Total Number of elements	61776
Triangular elements	61776
Quadrilateral	0
Boundary elements	3844
Vertex elements	12

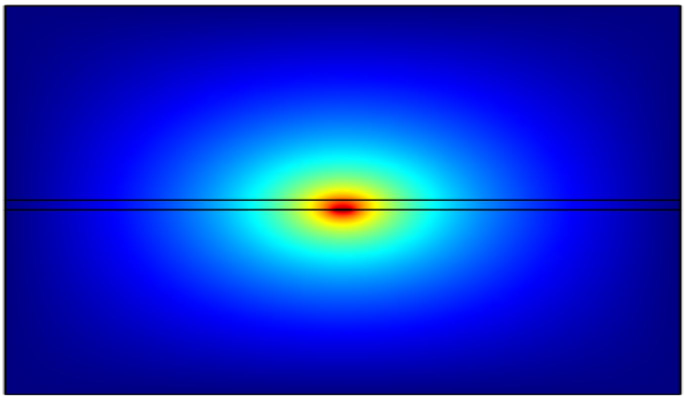

Figure 9. 2D surface potential distribution of shielded inverted microstrip line with $w = h$

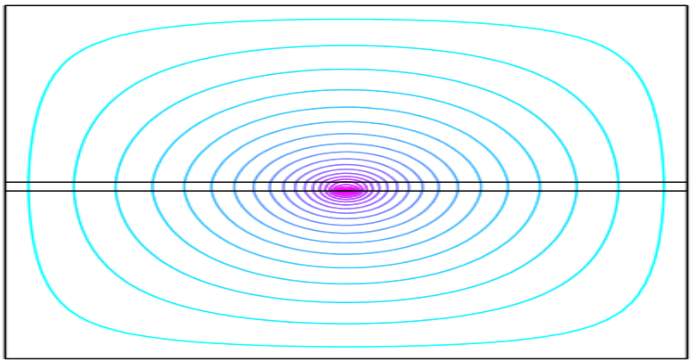

Figure 10. Contour plot of shielded inverted microstrip line with $w = h$

From the model, we generate the finite element mesh plot as in Fig. 8. Table 7 shows the statistical properties of the mesh. While, Fig. 9 shows the 2D surface potential distribution for $w=h$; although the contour plot is presented in Fig. 10 of the model. Figure 11 presents the electric potential plot as a function of arc-length. In addition, Fig. 12 shows the comparison analysis of potential distribution of the model with and without dielectric substrate. It observed that the peak value of electric potential is increased as the dielectric is placed in the substrate.

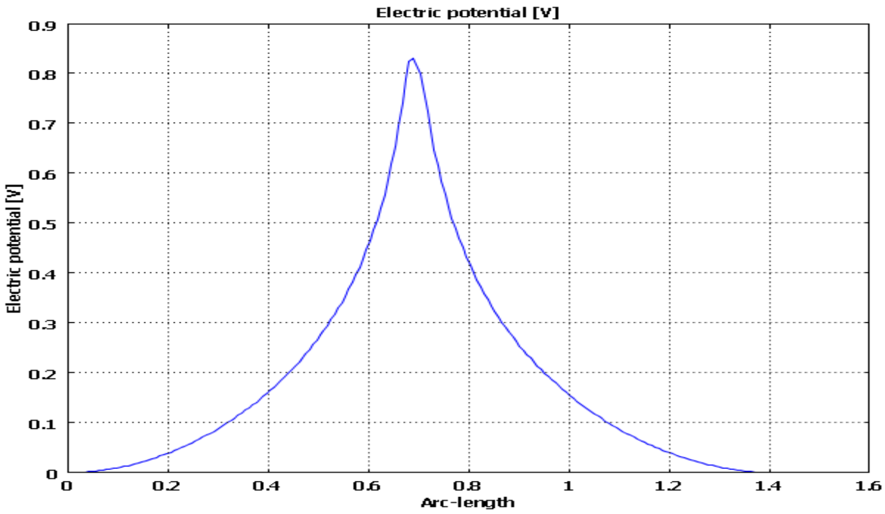

Figure 11. Potential distribution of shielded inverted microstrip line with $w = 5h$ from $(x, y) = (0,0)$ to $(x, y) = (1,1)$ mil

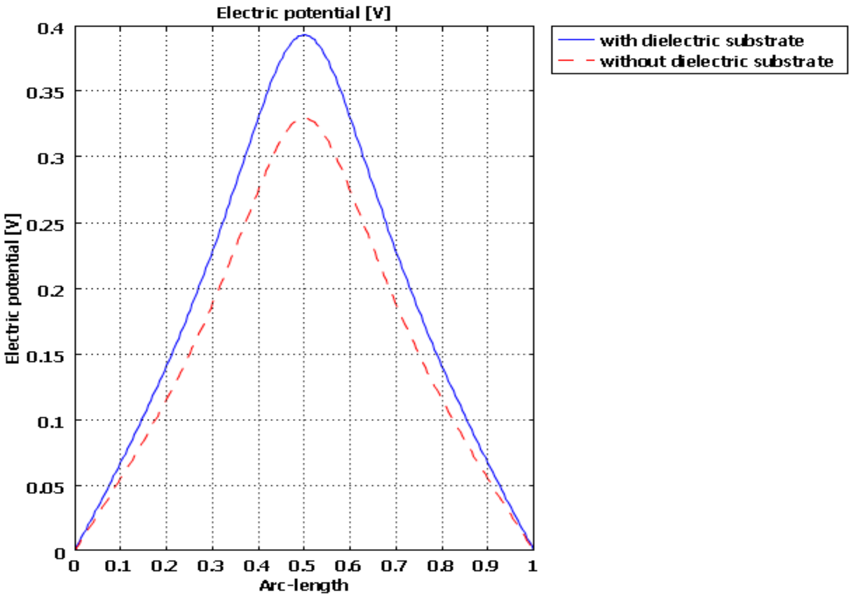

Figure 12. Potential distribution of shielded inverted microstrip line with $w = h$ at $y = 0.6$ mil

The simulation was done twice–once to calculate C when ε_r = 2.22, 9.8, and 12.9 and the other to calculate C_o when ε_r = 1.0. We need C_o to calculate the inductance L and the impedance Z_o according to eqs. (1) and (2) respectively. Tables 8, 9 and 10 show the finite element results for the capacitance per unit length C, the inductance per unit length L and characteristic impedance Z_o of shielded inverted microstrip line when ε_r = 2.22, 9.8, and 12.9 respectively. The results in Tables 8, 9, and 10 are very close in value compared to the shielded suspended microstrip line as in Tables 2, 3, 4 and 6.

Table 8. Capacitance, inductance, and characteristic impedance and of the shielded inverted microstrip line when $\varepsilon_r = 2.22$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)	(Z_o in Ω)
0.1	8.246	10.99	1.3475	350.18
1.0	12.49	15.32	0.8896	240.97
5.0	19.55	22.13	0.5683	160.30

Table 9. Capacitance, inductance, and characteristic impedance and of the shielded inverted microstrip line when $\varepsilon_r = 9.8$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)	(Z_o in Ω)
0.1	8.246	21.32	1.3475	251.31
1.0	12.49	25.57	0.8896	186.52
5.0	19.55	32.06	0.5683	133.14

Table 10. Capacitance, inductance, and characteristic impedance and of the shielded inverted microstrip line when $\varepsilon_r = 12.9$

w/h	C_o (pF/m)	C (pF/m)	L (μ H/m)	(Z_o in Ω)
0.1	8.246	24.59	1.3475	234.09
1.0	12.49	28.91	0.8896	175.44
5.0	19.55	35.53	0.5683	126.48

4. Conclusion

In this paper, we have presented the quasi-TEM analyses of two-dimensional shielded suspended microstrip line and shielded inverted microstrip line at dielectric constants ε_r = 2.22, 9.8, and 12.9. The results obtained using finite element method for the capacitance per unit length, inductance per unit length and characteristic impedance agree well with those found in the other methods. Also, we developed a new model for shielded inverted microstrip line and compared the results with shielded suspended microstrip line. We found them to be very close. In addition, we determine the quasi-TEM spectral for the potential distribution of the models.

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