Electromagnetic Wave Analysis of Waveguide and Shielded Microstripline

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Abstract: Electromagnetic wave analysis of waveguide has been done in this paper with the help of Finite Element Method (FEM) based COMSOL Multyphysics software. The design is further extended by placing conductor on a dielectric slab included in the waveguide to form a shielded microstrip transmission line. The simulated models are analyzed to determine the wave propagation characteristics. The validation is done by evaluating the critical frequency, propagation constant and transversal field distribution of modes at given phase constant β and angular frequency ω.

Keywords: Waveguide, Shielded Microstripline, Finite Element Method, Field Distribution, Critical Frequency

1. **Introduction**

Waveguide is a structure which guides waves such as electromagnetic waves and sound waves. Rectangular cross sections and circular ones are the most common structure. Metallic walls of waveguides are assumed to be perfectly electrically conductive, and the waveguides are expected to be filled in by air. In these structures, electromagnetic energy can propagate in the form of transversally electric waves (a component of the magnetic field intensity, which is oriented to the direction of propagation, is not zero) or transversally magnetic waves (electric field intensity component in the direction of propagation is non-zero). If a slab of dielectric material is placed into the waveguide, the electromagnetic field continuously passes from the dielectrics to the air and vice versa. This continuous field pass between different media can physically exist only if the electric field component in the direction of propagation and the magnetic one are both nonzero. This phenomenon describes the characteristics of the hybrid waves. These waves are very complicated and the exact analytic solution is unknown in this case.

The described field structure in the waveguide can become even more complicated if a metallic conductor is placed on the dielectric slice. In the structure electromagnetic field induces currents into the conductor, and those currents cause a mutual coupling of hybrid waves. These waves can be analyzed by using numerical methods only. The structure obtained is known as shielded microstrip transmission line. In the present work, the analysis of waveguide and shielded microstrip transmission line has been done using COMSOL Multiphysics package based on finite element method (FEM).

2. Design Methodology

For the mathematical description of wave propagation in microwave transmission lines Maxwell equations in the differential form can be used.

$\nabla X H = j\omega D + J_{ind} + J_{en}$ (1)

$\nabla X E = -j\omega\beta$ (2)

$\nabla . D = \rho$ (3)

$\nabla . B = 0$ (4)

Where $D = \epsilon E$ (5)

$B = \mu H$ (6)

$J = \sigma E$ (7)

Here E is electric field intensity
H is magnetic field intensity
D is electric flux density
B is magnetic flux density
J_{ind} is induced current density
J_{en} is the enforced current density
ω is angular frequency
ε is permittivity
μ is permeability

Consider the first and second Maxwell equation and assume zero excitation currents (the field is analyzed in a long distance from the sources). The field amplitude can vary in the directions x and y only. Assuming non-attenuated wave propagation in the direction z, the amplitude stays constant and the phase of the wave changes.

$E_z(x,y,z) = E(x,y) \exp(-j\beta z)$ (8)

Here β is the phase constant (the propagation constant) of a wave in a waveguide.
Substituting eq.(1) into eq.(2), based on assumption in eq.(8) and performing some mathematical manipulations, the wave equation can be obtained as

$$\partial^2E/\partial x^2 + \partial^2E/\partial y^2 + (k_0^2-\beta^2)E = 0 \qquad (9)$$

Where $k_0^2=\omega^2\mu_0\epsilon_0$ denotes the free space wave number in a vacuum.

The wave equation mathematically describes the propagation of an electromagnetic wave in the direction of z axis. The analysis of wave equation can be performed in two alternative methods.
First, the waveguide is analyzed at a given angular frequency ω to compute the wave number. The field distribution in the transversal cross section E and the propagation constant β for the angular frequency ω are the only unknowns here. And secondly, the waveguide is analyzed for a given phase constant β. Assuming the phase constant is zero and substituting this value to eq.(9), the analysis can produce critical wave numbers (consequently critical frequencies) and the transversal field distribution of modes, which can propagate in the waveguide.
Substituting β = 0 to eq.(9), the wave equation reduces to

$$\partial^2E/\partial x^2 + \partial^2E/\partial y^2 + k_0^2 E = 0 \qquad (10)$$

Since eq. (10) is a partial differential equation, FEM can be used for the analysis of the field distribution inside a waveguide.

2.1 Waveguide Modeling

In the modeling of hollow waveguide, the walls of waveguide are perfectly conductive and inside of the waveguide is vacuum. Electromagnetic wave propagation in such kind of transmission lines belongs to the category of Perpendicular Waves in COMSOL. Next, the polarization of computed waves either transversally electric (TE) or transversally magnetic (TM) can be selected for performing the eigenfrequency analysis. For this, the recommended value of propagation constant β is 0.001 rad/m.

The dimensions used for creating the geometry of waveguide is
Width of the waveguide is 0.02286 m
Height of the waveguide is 0.01016 m

The geometry of the waveguide model has been created in COMSOL using the dimensions mentioned above as shown in fig.1

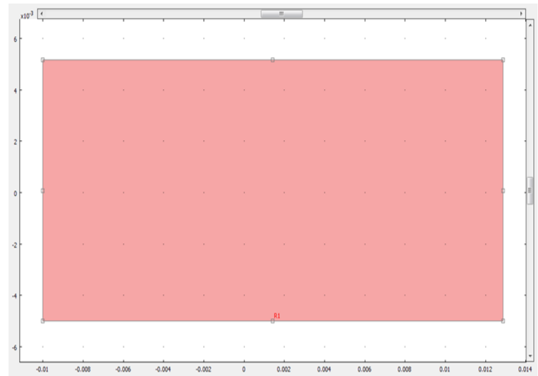

Fig.1 Geometry of waveguide

2.2 Simulation Results

After applying the boundary conditions meshing is performed by adaptive mesh refinement technique. After the refinement the structure is ready to solve.
The generated model is solved to obtain the computational result in the form of visualization of the field power density distribution of the lowest mode in the transversal cross section of the waveguide depicted in fig.2.
Higher modes can also be visualized in the post processing by appropriately selecting the parameter.

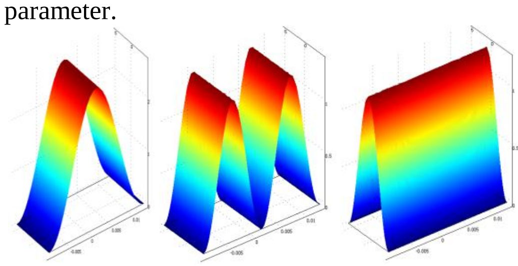

Fig.2 Field power density distribution of the modes TE_{10}, TE_{20}, TE_{01}

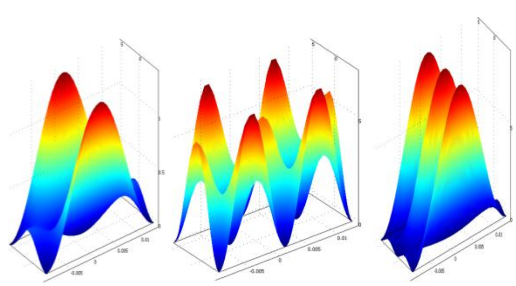

Fig.3 Various field power density distribution of the TM mode

2.3 Analysis of Shielded Microstrip Transmission Line

Hybrid modes propagate along the microstrip transmission line. If the critical frequency of modes propagating along the line is to be computed, eigenfrequency analysis is selected. Here interest is in parameters of a mode propagating at a given frequency f, and therefore, Mode Analysis is chosen.

The dimensions used for creating the geometry of shielded microstrip transmission line are:
Width of the outer conductor=12.7mm
Height of the outer conductor= 12.7mm
Width of the inner conductor= 1.27mm
Thickness of the inner conductor= 0.08mm
Height of the dielectric layer= 1.27mm
Permittivity of dielectric layer=4.2

The geometry of the shielded microstrip transmission line model shown in fig.4 has been created using the dimensions mentioned above.

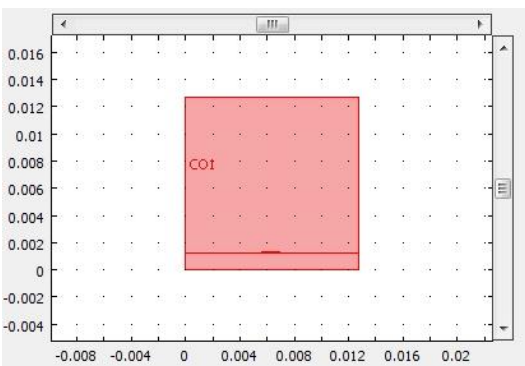

Fig.4 Geometry of shielded microstrip transmission line

2.4 Simulation Result

The frequency of the analysis is f = 10GHz.
After applying the boundary conditions again meshing is performed by adaptive mesh refinement technique and model is then executed. The 2D and 3D plots of field power density distribution of shielded microstrip transmission line are shown in fig.5 and fig.6 respectively.

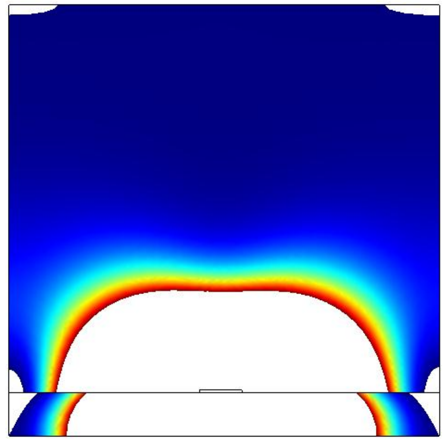

Fig.5 The 2D plot of field power density distribution of shielded microstrip transmission line at 10 GHz

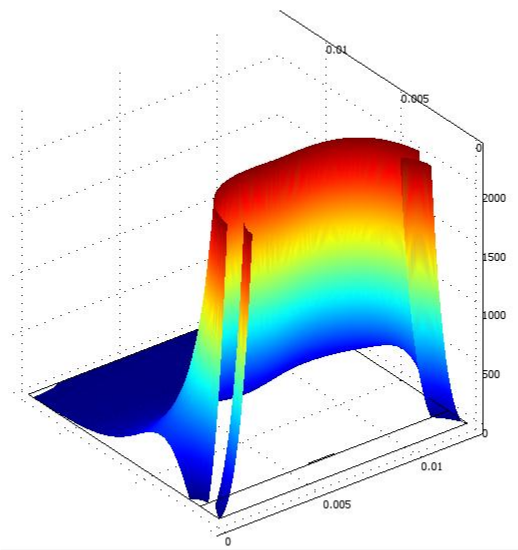

Fig.6 The 3D plot of field power density distribution of shielded microstrip transmission line at 10 GHz

The obtained field distribution is typical for the dominant quasi-TEM wave, the longitudinal component of the electric field intensity approaches, and transversal components seem to radiate from the microstrip (red arrows) shown in fig.7. The phase propagation constant of the dominant mode at the given frequency is 371 rad m^{-1}.

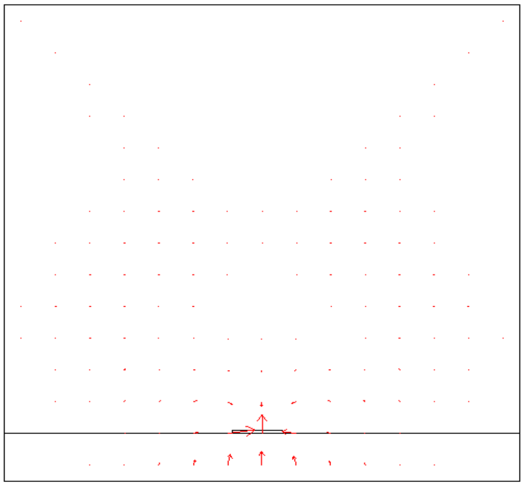

Fig.7 The Arrow plot of field power density distribution of shielded microstrip transmission line at 10 GHz.

If the frequency is increased to f2=20 GHz, different modes of different phase constants propagate along the transmission line. Waves therefore reach the end of the transmission line differently delayed, and here, they interfere. This phenomenon causes the signal distortion. The phase propagation constant of the dominant mode at the given frequency is 369.7530 radm^{-1}.

The 2D and 3D plots of field power density distribution of shielded microstrip transmission line at 20GHz are shown in fig.8 and fig.9.

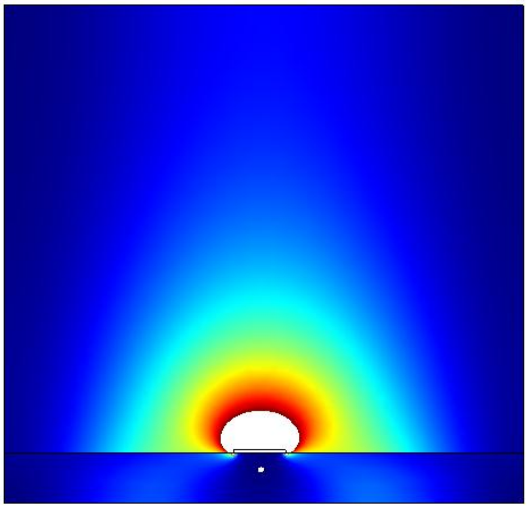

Fig.8 The 2D plot of field power density distribution of shielded microstrip transmission line at 20 GHz.

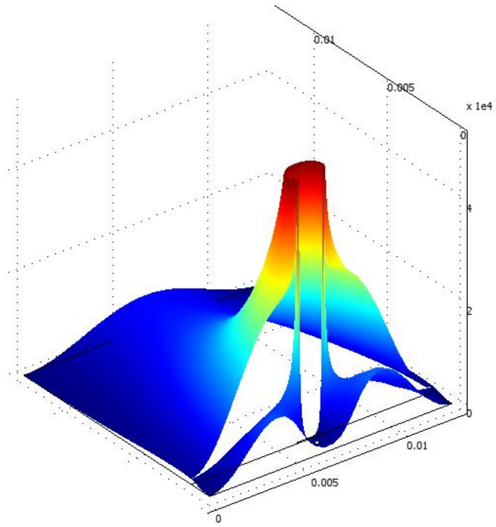

Fig.9 The 3D plot of field power density distribution of shielded microstrip transmission line at 20 GHz

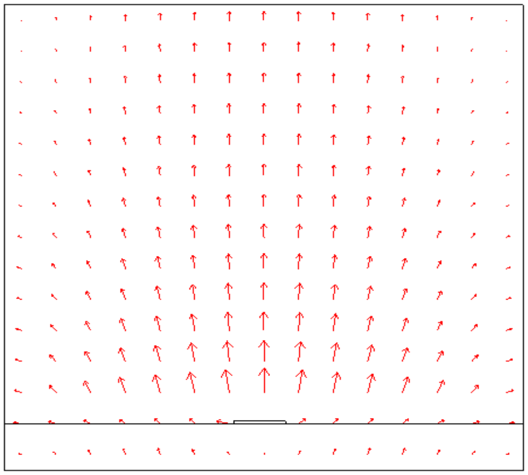

Fig.10 The Arrow plot of field power density distribution of shielded microstrip transmission line at 20 GHz.

3. Conclusions

In this paper electromagnetic analysis of waveguide and shielded microstrip transmission line are presented. Simulations are performed with the help of FEM based COMSOL Multyphysics Software. Field power density distribution of different TE and TM modes of waveguide are plotted and further field power density distribution of shielded microstripline at different two frequencies have been determined.

4. References

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