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Study of Dispersion Analysis for Various Microstrip Line Configurations Using Finite Difference Method

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ABSTRACT

In this paper, we studied about static analysis and losses of microwave isolated single stripline structure using conformal mapping method. Microstrip lines due to presence of two different dielectric boundaries does not support a pure TEM wave. It is assumed that only the fundamental mode will propagate, but the propagation constant, γ, is a nonlinear function of frequency. Due to the presence of two different dielectrics, the fringing fields experience an in-homogenous dielectric leading to a discontinuity on the field. A parameter called effective permittivity (ϵ_{eff}) is introduced, which is always lesser than the permittivity of the substrate as the fields exists both in air and the substrate. Due to the non-TEM nature of the fields, the effective permittivity is dependent on the frequency. This is due to the fact that more field lines will penetrate the substrate with increasing frequency thus increasing the effective permittivity.

Keywords : MICs, Dispersion, Microwave, Conformal Mapping Method.

1. Introduction

Quasi-static method used for low-frequency analysis doesn't predict the frequency dependence of the micro stripline transmission parameters. The deviation is due to the fact that hybrid modes get excited as frequency increases. The Quasi-static analysis does not take the higher order modes into account. The number of higher orders propagating modes increases with frequency [1-7]. ϵ_{eff} varies significantly over frequency thus leading to distortion in pulse shapes. A typical variation is shown in Fig 1. The velocity of propagation varies with $\epsilon_{eff}\ as\ v = c/\sqrt{\epsilon_{eff}(f)}$ where c is the velocity of light in vacuum. If a pulse is made of different spectral components, then each frequency component will travel with different velocities thus leading to the pulse shape distortion. Large variations in ϵ_{eff} are observed at wavelengths comparable to the transverse dimensions of the micro stripline. The variation in ϵ_{eff} has a direct bearing on the Z_0 as well, making even Z_0 a frequency dependent parameter. As the frequency increases higher modes start to contribute significantly.

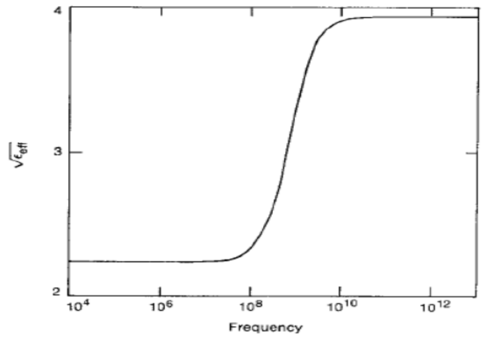

Fig. 1

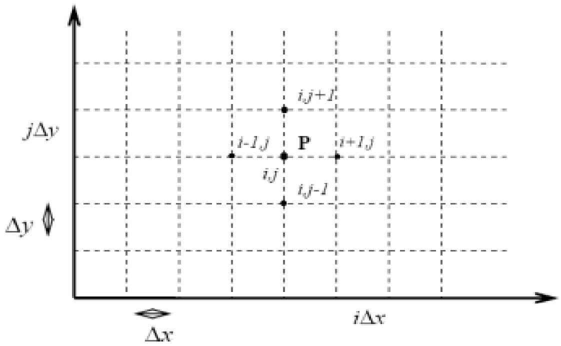

Fig. 2

Fig. 1. Variation of ϵ_{eff} with frequency for a microstrip of w = h = 1 and ϵ_r = 80 (water) [15]. Fig. 2. The region of analysis being divided into meshes

2. Finite Difference Method (FDM)

[8], [11] As we now know that the fundamental problem in finding Z_o for a given transmission line is the solution of either the Laplace equation.

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \qquad (1)$$

or the Poisson's equation

$$\nabla^2\phi = -\rho/\epsilon$$

An approximate solution for these equations can be obtained by using FDM. Well known basic techniques being the Newton's forward. Newton's backward difference formula and the central difference formula. For numerical computations. We divide the whole region of analysis into small discrete regions (a.k.a *meshers)*, each intersection of horizontal and vertical line, representing a node at which the value of the potential is determined. The difference between the potential at a node A and the note P can be represented as a infinite series using Taylor's theorem

$$\phi_B - \phi_P = \Delta_x\frac{\partial\phi}{\partial x} + \frac{(\Delta x)^2}{2!}\frac{\partial\phi}{\partial x^2} + \frac{(\Delta x)^3}{3!}\frac{\partial^3\ phi}{\partial x^3} = \cdots$$

and similarly, between another node B and P

$$\phi_A - \phi_P = \Delta_x\frac{\partial\phi}{\partial x} + \frac{(\Delta x)^2}{2!}\frac{\partial\phi}{\partial x^2} - \frac{(\Delta x)^3}{3!}\frac{\partial^3\phi}{\partial x^3} + \cdots$$

Neglecting the higher order terms,

$$\frac{\partial\phi}{\partial x^2} \approx \frac{\phi_A + \phi_B - 2\phi P}{(\Delta x)^2} \qquad (2)$$

(2) can be re-written using the notation shown in Fig 2

$$\frac{\partial\phi}{\partial x^2} \approx \frac{\phi(i+1,j) + \phi(i-1,j) - 2\phi(i,j)}{(\Delta x)^2} \qquad (3)$$

Using the same argument.

$$\frac{\partial^2\phi}{\partial x^2} \approx \frac{\phi(i,j+1) + \phi(i-1,j) - 2\phi(i,j)}{(\Delta x)^2} \qquad (4)$$

Taking $\Delta x = \Delta y = h$ and puttig (3) and (4) in (2)

$$[\phi(i+1,j) + \phi(i-1,j) + \phi(i,j-1) + \phi(i,j+1)] - 4\phi(i,j) = 0 \qquad (5)$$

or

$$\phi(i,j) = \frac{[\phi(i+1,j) + \phi(i-1,j) + \phi(i,j-1) + (i,j+1)]}{4}$$

Looking at (5), we can infer that the potential ϕ at a point is being approximated in terms of the potentials at its four neighbouring points. The original Laplace equation has now been approximated by a set of linear equations. The bottleneck in FDM is the solution of the large set of simulatneous equations.

There are two popular approaches to solve the simulataneous equations in FDM.

Band Matrix Method: (5) is applied to all the free nodes in the solution region. The set of simulataneous equations are then formulated as a matrix equation

AX = B

where A is the sparse matrix representing the relationship between the nodal voltages, X is a column vector containing the variable representating the unknown nodal voltages, and B being the right-hand side constants, which are obtained from the given boundary and initial conditions. The solution of the linear equation is then obtained by the use of Gauss-elimination method

$$X = A^{-1}B \quad (6)$$

Iterative method: One of the iterative methods is the successive over-relaxation method. Here we define the residual R(I,j) at the node. \ (I,j) denoting the error by which the value of $\phi(i,j)$ deviates from (33).

$$R(i,j) = \phi(i+1,j) + \phi(i-1,j) + \phi(i,j-1) + \phi(i,j+1) - 4\phi(i,j) \quad (7)$$

The value of the Residual at the k^{th} iteration is then propagated to the next iteration using.

$$\phi^{k+1}(i,j) = \phi^{k}(i,j) + \frac{\Omega}{4}R^{k}(i,j) \quad (8)$$

The method is convergent for values 0< Ω < 2. and repaidly convergent for 1< $\Omega < 2(11)$. The optimum value of Ω usually found out on trial-and-error basis.

Any of these two methods can be used to determine the value of the potential ϕ. The value of ϕ will then be used to determine the value of the charge on the conductor.

$$Q = \epsilon_o \epsilon_r \sum\sum\left(\frac{\delta\phi}{\partial n}\right) \quad (9)$$

The double summation in (7) covers the entire cross section of the transmission line. $\frac{\partial\phi}{\partial n}$ is approximated as

$$\frac{\partial\phi}{\partial n} = \frac{\phi(i+i,j) - \phi(i,j)}{\Delta x}$$

The value of the capacitance is then C=Q/V, where the V_t is the voltage applied between the plates of a stripline. The air Capacitance C_a can be found out by putting $\epsilon_r = 1\ in\ (7)$

The accuracy of FDM relies on the fineness of the mesh. Finer the mesh better will be accuracy of the solution. The algorithm usually starts with a coarse mesh and then advances to a finer net. Coupled lines usually need finer mesh as the field variations are significant at the edges of the strip.

3. Dispersion Analysis

The cutoff frequency above which the first longitudinal mode (TE) begins to contribute significantly is approximately given by (9)

$$f_{TE} = c/\left(4h\sqrt{\epsilon_r - 1}\right) \quad (10)$$

Operating the micro stripline above this frequency leads to what is known as *modal dispersion*. 10 shows that the effective range of quasi-static analysis reduces with increasing ϵ_r. This also means that the frequency range of operation decreases with increasing ϵ_r.

Various analytical, empirical and semi-empirical methods are employed to study the dispersion effects. Some of them are: Spectral domain immittance method, The integral equation method, Finite difference techniques, Modal analysis, Method of lines, Planar waveguide model

3.1. Spectral domain analysis

In this method, a set of algebraic functions is formulated relating the Fourier transform of the currents on the strip conductors to that of the fields at the dielectric interface in the plane of the conductor [2].

3.2. Method of Lines

[17], [18] For a Partial Differential Equation, the principle lies in the discretization of all but one of the independent variables to obtain a set of ordinary differential equations or difference equations. The procedure is also known as "semidiscretization by the method of lines". Consider the scalar potential $\varphi^{(e)}$ and $\varphi^{(h)}$ satisfying the Helmoltz' equation

$$\frac{\partial^2\phi^{(e,h)}}{\partial x^2} + \frac{\partial^2\phi^{(e,h)}}{\partial y^2} + (k^2 - \beta^2)\phi^{(e,h)} = 0 \quad (11)$$

We begin with discretizing the $x - axis$, which is done by drawing N parallel lines along $y - axis$. Let the spacing between the lines be same and be equal to h. Now due to the discretization, the potential ϕ is now divided into a set of N value $\phi_1, \phi_2, \dots, \phi_N)$ at the lines $x_i = x_0 + ih, = 1,2,\dots,N$. The discretization then yields a set of N coupled ordinary differential equations

$$\frac{\partial^2\phi_i}{\partial y^2} + \frac{1}{h^2}\left[\phi_{i-1}(y) - 2\phi_i(y) + \phi_{i+1}(y)\right] + (k^2 - \beta^2)\phi_i(y) = 0, i = 0,1,\dots,N \quad (12)$$

with the constant p_1 and p_2 representing the boundary conditions. We have (12) as

$$h^2\frac{\partial^2\vec{\phi}}{\partial y^2} - [P - h^2(k^2 - \beta^2)I]\vec{\phi} = 0 \quad (13)$$

where I is the identity matrix. The potential vector $\vec{\phi}$ is then transformed using the orthogonalizing vector T^t such that

$$T^t\vec{\phi} = \vec{U}$$

Using this (12) will then be

$$h^2\frac{\partial^2\phi_i}{\partial y^2} - [\lambda_i - h^2(k^2-\beta^2)U_i = 0, i = 0,1,\dots,N]$$

where $\lambda_i s$ are the eigen values of P. The resulting uncoupled differential equations are then solved for ϕ.

Due to the presence of the edge singularities in the strip conductors, there is usually a discretization error associated with it. This can however be minimized by ensuring that the edge conditions are met, which states that the strip should exceed the last $\varphi^{(h)}$ line by $\frac{3h}{4}$ and the last $\phi^{(e)}$ line by $\frac{h}{4}$ [17]. These edge conditions are difficult to be met in the case of multiple conductor lines and strips with small strip dimensions. A modified method of lines has been suggested which transforms the given strip configuration to another dimension where the edge conditions can possibly be met. This is achieved by the use of some transformation functions [19].

4. Dispersion analysis for various microstrip line configurations

The frequency dependence of the transmission parameters will be studied. Closed form expressions shall be provided wherever available for the dispersive effects on Z_0 and ϵ_{eff}

4.1. Microstrip lines

The Dispersion analysis is done in two ways. In the first category, an equivalent parallel plate model of the waveguide is used which is then used to analyse the frequency dependence. The following observations are made regarding the dispersive effects in the Microstrip (13).

(i) The normalized phase velocity v_p/v is a monotonically decreasing function of frequency

(ii) The normalized phase velocity and its first derivative at $f = 0$ are given by

$$\bar{v}_p = v_p/v|f = 0 = \frac{1}{\sqrt{\epsilon_{eff}}}$$

and

$$\left.\frac{d\bar{v}_p}{df}\right|_{f=0} = 0$$

(iii) The normalized phase velocity and its first derivative as $f \to \infty$ are given by

$$\bar{v}_p = \frac{v_p}{v|_{f\to\infty}} = \frac{1}{\sqrt{\epsilon_r}}$$

and

$$\left.\frac{d\bar{v}_p}{df}\right|_{f\to\infty} = 0$$

The second being the solution of field problem in spectral domain and then using the power-current definition for Z_0. The Dispersion model is based on considering the microstrip as a Longitudinal-section Electric (LSE) (14). The procedure begins with modeling the given microstrip as an LSE with a modified structure to aid in analysis. The modified structure then is made to take the Zero-frequency electrical parameters. A transverse resonance analysis of the model relates ϵ_{eff} is then obtained as (14).

$$\epsilon_{eff}(f) = \epsilon_r - \frac{\epsilon_r - \epsilon_{eff}(0)}{1+G(f/f_p)^2} \tag{15}$$

where

$$f_p = \frac{Z_0}{2\mu_0 b}$$

has quoted that G approaches unity according to the experimental results, but the modified expressions are [1].

$$Z_0(f) = Z_{0T} - \frac{Z_{0T} - Z_0(0)}{1+G(f/f_p)^2} \tag{16}$$

where Z_{0T} is twice the characteristic impedance of a stripline of width W and height 2h and

$$G = \sqrt{\frac{Z_0 - 5}{60} + 0.004Z_0}$$

and

$$f_p(GHz) = 15.66Z_0/h$$

An alternative set of expression have been derived based on the coupling of the surface wave and the LSE modes. The expression is (15)

$$\epsilon_{eff}(f) = \epsilon_r - \frac{K_1(\epsilon_r - \epsilon_{eff}(0))}{1 + K_2(f/f_p)^2} \quad (17)$$

where

$$f_p = \frac{Z_0}{2\mu_0 b}$$

$$K_1 = \frac{\epsilon_r - \epsilon_{II}}{\epsilon_r - I}$$

and

$$K_2 = \frac{\pi^2 K_1 \left(\epsilon_r - \epsilon_{eff}(0)\right) \epsilon_{eff}(0) - 1)(\epsilon_r - \epsilon_{II})}{(\epsilon_r - I)^2 \epsilon_{eff}(0)}$$

and

$$\epsilon_{II} = \epsilon_r + (s_1 + s_2 - a_2/3)k_0^2$$

$$s_1 = 3\sqrt{\eta_2 + \eta_1^3 + \eta_2^2}$$

$$s_1 = 3\sqrt{\eta_2 - \eta_1^3 + \eta_2^2}$$

and

$$\eta_1 = a_1/3 - a_2^2/9$$

$$\eta_2 = (a_1 a_2 - 3a_0)/6 - a_2^3/27$$

a_i s are give by

$$a_2 = (2p + qp^2 - r)/p^2$$

$$a_1 = (2pq + 1)/p^2$$

$$a_0 = q/p^2$$

$$p = b/3$$

$$q = (\epsilon_r - I)k_0^2$$

$$r = (b/\epsilon_r)^2$$

Another approach for dispersion analysis has been used in [36] using the so-called Logistic Dispersion Model (LDM) which makes use of the basic statement that *the rate of increase of effective dielectric constant with frequency* ∝ *[Effective relative permittivity at the given frequency]* × *[Remaining fractional relative permittivity of the substrate]*

4.2. Coupled microstrip lines

A semi-empirical dispersion model has been used for the modeling. The model consists of an equivalent coupled parallel-plate waveguide filled with the corresponding dielectric. This structure is then analysed in terms of the quasi-static line impedances and capacitances. The frequency dependence of these parameters are then assumed to be similar to that of a microstrip.

Expressions similar to Gentsinger's relations are given as [10].

$$\epsilon_{eff}^i(f) = \epsilon_r - \frac{\epsilon_r - \epsilon_{eff}^i(0)}{1 + G(f/f_p)^2}$$

where

$$G = \begin{cases} 0.6 + 0.018 Z_{0_0} & odd\ mode \\ 0.6 + 0.045\, Z_{0_e} & even\ mode \end{cases}$$

and

$$f_p = \begin{cases} 31.32 Z_{0_0}/h & odd\ mode \\ 7.83\, Z_{0_e}/h & even\ mode \end{cases}$$

Similar equations holds for Z_{0_i}, which are (26)

$$Z_{0_i}(f) = \frac{Z_{Ti} - Z_{0_i}(o)}{1 + G(f/f_p)^2}$$

where Z_{Ti} is the impedance of a coupled stripline with gap s and width of the strip w and spacing between the ground planes $2h$.

$$Z_{Ti} = \frac{60\pi\, K(k_i)}{\sqrt{\epsilon_r}\, K(k_i')}$$

where

$$k_i = \begin{cases} tanh\left(\frac{\pi W}{4h}\right)/tanh\left(\frac{\pi(W+s)}{4h}\right) & odd\ \ mode \\ tanh\left(\frac{\pi W}{4h}\right) tanh\left(\frac{\pi(W+s)}{4h}\right) & even\ \ mode \end{cases}$$

4.3. Suspended microstrip lines

Suspended Microstrip lines are relatively low-dispersion lines, but the flowing observations hold (17). For a given *W/b* and *a/b*, the effects of dispersion are more pronounced as ϵ_r increases. For a given ϵ_r and *a/b*, the effects of dispersion decreases with *W/b*. For a given ϵ_r and *W/b*, no simple relationship exists between the dispersion effects and *a/b*. Dependence of the effects of dispersion on t is negligibly small.

The following design equations are developed based on the modeling of the frequency dependence to match the Spectral-domain full-wave analysis (18)

$$\epsilon_{eff}(f) = \frac{\epsilon_{eff}(0) + K_\epsilon \epsilon_r}{1 + K_\epsilon}$$

where

$$K_\epsilon = \sum_{i=0}^{4} (c_i(\epsilon_r, a/b, w/b))(f/f_p)^i$$

$$f_p = \frac{Z_0}{2\mu_0(a+b)} \frac{a}{0.064}$$

c_i s is given by (17). Dispersive effects of Z_o is given by (18)

$$Z_o(f) = \frac{120\pi(a+b)}{W_e(f)\sqrt{\epsilon_{eff}(f)}} \frac{a}{0.074}$$

where $W_e(f)$ is the width of the equivalent planar waveguide given by the solution of the equation

$$\sum_{i=0}^{4} F_i(W_e(f)/\lambda)^i = 0$$

where λ is the free-space wavelength in cm. All the dimensions in cm.

$$F_o = d_0 W/\lambda$$

$$F_1 = -d_0 - 2\left(\frac{W_e(0)}{\lambda} - d_1\frac{W}{\lambda}\right)\sqrt{\epsilon_{eff}}$$

$$F_2 = 2(1-d_1)\sqrt{\epsilon_{eff}} + 4d_2\frac{W}{\lambda}\epsilon_{eff}$$

$$F_2 = -4\left(d_2 - 2d_3\frac{W}{\lambda}\sqrt{\epsilon_{eff}}\right)\epsilon_{eff}$$

$$F_4 = -8d_3\epsilon_{eff}\sqrt{\epsilon_{eff}}$$

and

$$W_e(0) = \frac{120\pi(a+b)}{Z_0\sqrt{\epsilon_0}} \frac{a}{0.064}$$

expressions for d are given in (18).

4.4. Inverted microstrip line

[38] suggests the same set of expressions used in the previous subsection holds good for inverted microstrip lines as well.

5. Conclusions

Dispersion analysis for several microstrip lines are absent as closed-form expressions were not available for these. Dispersive effects on Dielectric and Conductor losses has also been omitted in the discussion. All the static equations given here were tested against various other transmission line calculators available. The equations were implemented as a part of the Microwave transmission line tool. An excellent reference for the various analysis equations is [39-41].

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