PLANAR MEANDERLINE FERRITE PHASE SHIFTERS WITH MULTI-LAYER FERRITE/ DIELECTRIC IMBEDDING

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Summary

This paper presents methods for rapid analysis of coupled lines in composite ferrite/dielectric materials. New expressions are given for the calculation of effective dielectric constants showing a linear relationship with respect to the dielectric constants of the materials in the structure. A similar linearity is shown to characterize the effective relative permeabilities. Conditions for matching of meanderlines are presented which are used in computer programs for the design of meanderline ferrite phase shifters.

Measured characteristics of a phase shifter with a four layer ferrite/dielectric imbedding are presented. The phase shifter is well matched in the vicinity of the frequency for maximum differential phase shift. An optimum figure of merit ranging from 340 to 390°/dB for various magnetizations was obtained.

Introduction

Ferrite phase shifters based on meander-folded lines have been known for several years. In 1966 Jones described the design of a stripline phase shifter[1] by using the theories of Bolljahn and Matthaei.[2] A couple of years later Roome and Hair[3] gave a first order theory for the functioning of reciprocal as well as non-reciprocal phase shifters in MIC-techniques. In separating the meanderline from the ferrite by a thin dielectric sheet the peakpower capability was shown to increase.[4] Thereby both the total losses and the differential phase shift were found to decrease. However, by choosing a proper combination of materials and geometry a net improvement of the figure of merit was achieved.[5] Thus, experimental results indicate that optimal performance of the meanderline phase shifter demands a multi-layer structure. In this paper the design of meanderline phase shifters with inhomogeneous constructions will be discussed. Our main interest will be concentrated on the structure shown in Fig 1.

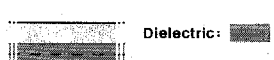

Fig 1 Meanderline imbedded in a ferrite/dielectric composite

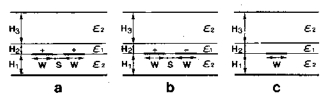

Fig 2 Basic multi-layer structures for the design of meanderline phase shifters with composite media.

Design of meanderlines surrounded by ferrite/dielectric

Existing methods for analysis of coupled line structures imbedded in composite media are in general too slow to be convenient for use in a design procedure. By making use of proper approximations we shall here develop methods such that the computing efforts for synthesis are kept within acceptable limits.

Analysis of a single and two coupled lines

The structures to be studied, see Fig 2, are chosen as a starting point for the treatment of the meanderline in Fig 1. They can be analysed by the use of, for instance, the method of Lennartsson.[6] The properties of the lines are here described by the filling factors, α_{de}, α_{do} and α_s, and the characteristic admittances for the lines imbedded in vacuum, Y_{vde}, Y_{vdo} and Y_{vs}. The indices de, do and s indicate properties connected with the even and odd mode excitations of the double line and the single line, respectively. We define the filling factor, α in relation to the effective dielectric constant, ε_{eff}, according to

$$\alpha = \frac{\varepsilon_{eff} - \varepsilon_2}{\varepsilon_1 - \varepsilon_2} \tag{1}$$

By considering the line width, W, as a variable and the other parameters of the structures as constants we can expand each one of the six characterizing parameters in a power series in W, thereby approximating the actual behaviour over a limited line width interval. If the structures are analysed for N different value of W, $W_1 \ldots W_N$, we can fit polynomial approximations of the order N-1 to the obtained parameter values resulting in the following equation system:

$$[W_a][C] = [S] \tag{2}$$

where

$$[W_a] = \begin{bmatrix} W_1^{\,0} & W_1^{\,1} & \ldots & W_1^{\,N-1} \\ W_2^{\,0} & W_2^{\,1} & \ldots & W_2^{\,N-1} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ W_N^{\,0} & W_N^{\,1} & & W_N^{\,N-1} \end{bmatrix}$$

[C] is a coefficient matrix and [S] is the matrix formed by the N analysis result vectors.

By solving (2) for the coefficient matrix [C] we get

$$[C] = [W_a]^{-1}[S] \tag{3}$$

When [C] is obtained, the structures can be analysed for an arbitrary line width, W, in the interval according to

$$[R] = [W_b][C] \tag{4}$$

where

$$[W_b] = [W^0 \quad W^1 \quad \ldots \quad W^{N-1}]$$

and

$$[R] = [\alpha_e(W) \quad \alpha_o(W) \quad \alpha_s(W) \quad Y_{vde}(W) \quad Y_{vdo}(W) \quad Y_{vs}(W)]$$

Based on the coefficient matrix [C] and Eq (4) the analysis can be performed several orders of magnitude faster than by direct use of, for instance, a finite difference method.[6]

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Derivation of TEM-characteristics for multiple lines

The properties of an infinite meanderline can be expressed in terms of the phase increment, φ, per unit cell assuming two normal modes of propagation, namely an even mode and an odd mode.[7] In the case with $\varphi = \pi$, which is of interest for the meanderline application here, magnetic and electric walls are centered between the lines as shown in Fig 3. In addition, we assume as

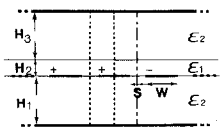

Fig 3 Infinite coupled line structure in a layered dielectric with even or odd excitation.

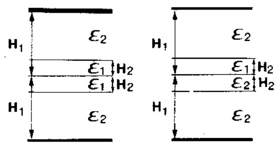

Fig 4 Multi-layer dielectrics.

a first order approximation that magnetic walls go through the middle of the lines. Then it can be shown[8] that the filling factor, $\alpha_{e,o}$, and the characteristic admittance $Y_{e,o}$ of the lines in Fig 3 can be expressed in terms of the corresponding characteristics of the lines in Fig 2 according to:

$$\alpha_{e,o} = \frac{\alpha_{de} Y_{dev} + \alpha_{do} Y_{dov} - \alpha_s Y_{sv}}{Y_{dev} + Y_{dov} - Y_{sv}} \tag{5}$$

$$Y_{e,o} = \sqrt{(Y_{dev}+Y_{dov}-Y_{sv})(\alpha_{de} Y_{dev}+\alpha_{do} Y_{dov}-\alpha_s Y_{sv})} \tag{6}$$

In analyzing coupled lines in layered dielectric/air structures Pompei et al.[9] noticed that the diagonalized capacitance matrix is a linear function of the dielectric constant. By superimposing structures with the same geometry but filled with different dielectric/air composites it has been shown[8] that a similar linearity is valid for coupled lines in a layered dielectric/dielectric structure. It has been deduced as a consequence that filling factors as defined above depend on the dimensions of the structures but are independent of the dielectric constants of the materials.[8]

By using the method of superposition of structures it has also been found[8] that the filling factors related to coupled lines with a given excitation centered in the structures in Fig 4a and b, α_a and α_b, respectively, are related as

$$\alpha_a = 2\alpha_b \tag{7}$$

Eq (7) gives the relation between characteristics calculated for the three-layer dielectric structures treated above and those of corresponding four layer structures.

Based on the duality of the permittivity and the permeability in Maxwells equations the following relation has been derived[8] between the effective dielectric constant, ε_{eff}, and the effective relative permeability, μ_{eff}, related to coupled lines with even or odd excitation in a layered magnetic/magnetic structure.

$$\mu_{eff}(\mu_1,\mu_2) = \left[\varepsilon_{eff}\left(\mu_1^{-1},\ \mu_2^{-1}\right)\right]^{-1} \tag{8}$$

where μ_1 and μ_2 are the relative permeabilities of the two magnetic materials. Eq (8) is an extension of a similar expression by Massé and Pucel[10] for a microstrip line on ferrite. By the use of Eq (8) the above summarized methods for calculation of effective dielectric constants can be applied to the calculation of effective relative permeabilities. Thus, for given configuration and excitation we can use the same filling factor in both cases:

If

$$\varepsilon_{eff}(\alpha) = (\varepsilon_1 - \varepsilon_2)\alpha + \varepsilon_2 \tag{9}$$

then

$$\mu_{eff}(\alpha) = \left[(\mu_1^{-1} - \mu_2^{-1})\alpha + \mu_2^{-1}\right]^{-1} \tag{10}$$

Thereby we have obtained effective means for the analysis of the meanderline phase shifter structure in Fig 1.

Matching conditions

In his analysis of infinite meanderlines Weiss[7] satisfied the boundary conditions given by the connecting links between the strips by superposition of the normal modes of propagation in an infinite array of corresponding strips. The solution of this problem leads to determination of the dispersion relation and the image admittance, Y_{im}, for the meanderline

$$\tan^2\frac{\varphi}{4} = \frac{Y_e}{Y_o}\tan\frac{\Theta_e}{2}\tan\frac{\Theta_o}{2} \tag{11}$$

$$Y_{im} = \sqrt{Y_e Y_o \frac{\tan(\Theta_e/2)}{\tan(\Theta_o/2)}} \tag{12}$$

where Θ_e and Θ_o are the electric lengths of the strips with even and odd mode excitation, respectively. At the matching frequency where φ and π, the even and odd mode admittances and propagation velocities are shown to coincide. Thus the design conditions are

$$\Theta_e = \Theta_o = \frac{\pi}{2} \tag{13}$$

$$Y_e = Y_o = Y_{in} \tag{14}$$

where Y_{in} is the matching admittance. Due to the fact that the coupling between nonadjacent lines is small compared with the coupling between adjacent lines and the coupling between the lines and the groundplanes the conditions (13) and (14) can be applied to all interior strips of finite meanderlines. For the same reason the matching conditions for the edge strips are similar to those of a corresponding C-section. The insertion phase shift, φ', of a C-section in composite materials is given by[11]

$$\tan^2\frac{\varphi'}{2} = \frac{Y_e}{Y_o}\tan\Theta_e\tan\Theta_o \tag{15}$$

where $Y_e \neq Y_o$ and $\Theta_e \neq \Theta_o$. For a striplength such that $\Theta_e \approx \pi/2$ and $\Theta_o \approx \pi/2$, we find from (15) that the propagation will be cut off within a frequency band in the vicinity of the design frequency. This stop band can be avoided by dividing the edge strips into sections with proper characteristic admittance levels[12], see Fig 5. The design equations are

$$Y_{e1a}\cdot Y_{o1a} = \frac{\Theta_{e1a}}{\Theta_{o1a}}\cdot Y_{in}^2 \tag{16}$$

$$Y_{e1b}\cdot Y_{o1b} = \frac{\Theta_{e1b}}{\Theta_{o1b}}\cdot\frac{\tan^2\Theta_{o1b}}{\tan^2\Theta_{e1b}}\cdot Y_{in}^2 \tag{17}$$

$$\Theta_{e1a} + \Theta_{o1a} = \Theta_{e1b} + \Theta_{o1b} = \frac{\pi}{2} \tag{18}$$

where the indices refer to the corresponding strip section. As indicated in Fig 5 the different widths of the sections 1a and 1b may require a corresponding partitioning of strip 2 to satisfy (14) with desired accuracy.

Synthesis routine

The synthesis of the phase shifter structure according to Fig 1 starts by the calculation of the coefficient matrix [C] given by (3). It can be observed that the concept of filling factors implies that [C] is independent of the material properties. Thus, the same coefficient matrix can be used for the optimization of phase shifter structures with different ferrite/dielectric combinations if the geometry is maintained. By the aid of (5) the filling factors of lines with coupling at both the edges are given and (7) is a basis for calculation of the filling factors for double dielectrics. The corresponding effective dielectric constants and relative permeabilities are obtained from expressions such as (9) and (10). When adjacent lines have different widths the coupling between the lines is taken as the geometric mean value of the couplings between the corresponding equally wide lines. The widths of the lines in the meander are then varied until the matching conditions are satisfied. The coupling between non-adjacent lines can be estimated to a first order of approximation by using an analysis program for homogeneous material. The dielectric constant and the relative permeability are thereby given as mean values of the effective ones for the meander sections. The coupling is then accounted for in a new synthesis of the meanderline.

Experiments

An experimental phase shifter was built according to a design based on the above method. The ferrite substrates were made of the material TT1-2650 from Trans Tech, Inc. with saturation and remanence magnetizations equal to 0.265 T and 0.151 T, respectively, at 20°C. The dielectric was copper clad RT/Duroid 5880, 0.005 inch thick, manufactured by Rogers Corporation, from which the circuit pattern was photo etched. The measured performance is shown in Fig 6. The mean figure

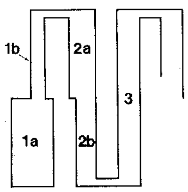

Fig 5 Stepped admittance design of the meanderline edge sections.

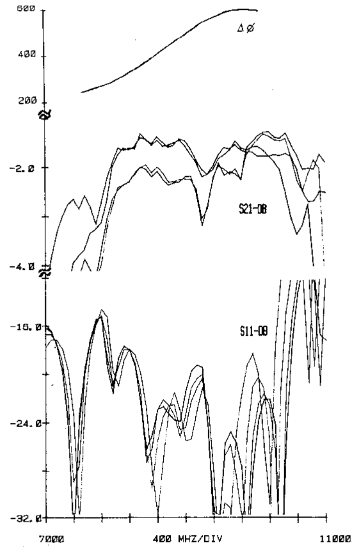

Fig 6 Measured performance of the experimental meanderline phase shifter for different magnetizations.

of merit is 310°/dB in the frequency interval 9.4 - 10.0 GHz with a maximum of 360°/dB at 10.0 GHz. The measured temperature dependence of the insertion phase at the two states of maximum remanent magnetization is -1.7 deg/°C and -2.2 deg/°C and thus the temperature dependence of the differential phase shift is 0.5 deg/°C, approximately constant over 9.4 to 10.0 GHz. The peakpower threshold was measured to be 40 W at 9 GHz and 60 W at 9.3 GHz.

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