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The improvement of Tri-Plate Performance by using corrugated transitions

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Abstract

A novel structure is investigated for the improvement of Tri-Plate performance. Based on the experience in the design of horn antennas, we introduce corrugations of the transition section of the Tri-Plate in order to achieve better field uniformity and to reduce the return loss. A corrugated transition waveguide may be viewed as the cascade of bifurcated metal waveguides, and we employed the building-block approach which breaks the overall structure into cascaded sub-cells, each of which may be analyzed rigorously by the mode-matching method. Thus, the input-output relation of each sub-cell is obtained and so is that of the overall structure. This enables us to carry out a parameteric study on the field distribution inside the Tri-Plate, so that we can optimize its design for any required specifications.

1. Introduction

A Tri-Plate is designed to generate a uniform electric field on the transverse plane for the EMS (Electromagnetic Susceptibility) testing. The fields are transferred through a taper transition from a small parallel-plate waveguide (ppwg) to a large ppwg, in which an EUT (equipment under test) is placed. However, the shape of taper transition should be well designed to maintain the field uniformity inside the uniform region; that is, to reduce the return loss and to suppress the excitation of higher-order modes.

In this paper, the taper transition of a Tri-Plate is viewed as a horn antenna and the technique of corrugated horn antenna is employed for the design of Tri-Plates with fins. We observe that a Tri-Plate with fins may be considered as the cascade of different sub-cells, each of which contains a finite length of uniform metal waveguide and a bifurcated metal waveguide. To simplify the formulation of this problem, we adapt the building-block approach, such that the input-output relation of each sub-cell is obtained first by the rigorous mode-matching method. And then, the results so obtained are combined to yield the input-output relation of the overall structure.

2. Statement of the problem

As described in the preceding section, the functions of the taper transition are used to reduce the return loss and to suppress the excitation of higher-order modes. However, in this paper, stress is placed on the characteristics of wave propagation in the transition region. The structure of non-uniform ppwg with fins is considered as a prototype to study the physical mechanism in order to develop criteria of design for the Tri-Plate with fins. As shown in Fig. 1, the structure is constructed as the cascade of sub-cells, each of which consists of a bifurcated waveguide and a uniform waveguide of finite length. To prove the low

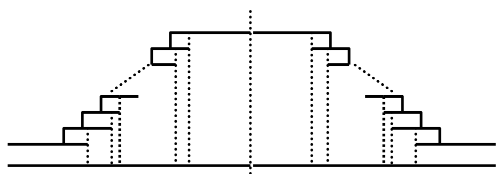

Fig. 1

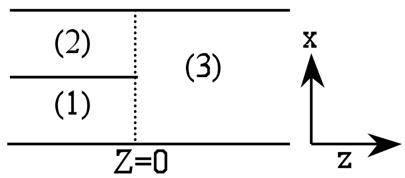

Fig. 2

return-loss and fields uniformity of the new structure, we compare the results of taper transitions with and without fins. The commonly used structure without fins is approximated by the staircase approximation. It is noted that such a structure may be considered as the degenerate case of the bifurcated discontinuity shown in Fig. 1 with diminishing fins.

3. Method of analysis

Returning to Fig. 1, we employ the building-block approach to simplify the analysis of this boundary value problem. Firstly, the input-output relation of the bifurcated PPWG, which is shown in Fig. 2, will be constructed by using the rigorous mode-matching method. Secondly, the input-output relation of the simple PPWG of finite length is well known and is skipped here. Finally, the field analysis of the cascaded sub-cells will be conducted, as given below.

3.1 Input-Output Relations of Bifurcated PPWG

For convenience of discussion, we assume that there is no variation of the structure and the fields along the y-direction. Therefore, the y-dependence of the fields is eliminated throughout the derivation. Referring to Fig. 2, we observe that the tangential fields at the discontinuity consist of the x and y components, which will be considered explicitly here. The general field solution in each constituent region will be expressed in terms of the superposition of the complete set of PPWG modes. For the tangential components of TM mode in a PPWG region, we have

$$E_x^{(i)}(x,z) = \sum_{n=0}^{n=+\infty} V_n^{(i)}(z)\cdot\phi_n^{(i)}(x) \qquad (1)$$

$$H_y^{(i)}(x,z) = -\sum_{n=0}^{n=+\infty} I_n^{(i)}(z)\cdot\phi_n^{(i)}(x) \qquad (2)$$

where i denoted the region 1, 2, and 3, respectively. $\phi_n^{(i)}(y)$ is the n^{th} TM mode function in PPWG. $V_n^{(i)}(z)$ and $I_n^{(i)}(z)$ can be interpreted as the voltage and current satisfying the transmission-line equations:

$$\frac{dV_n^{(i)}(z)}{dz} = -jk_{z,n}^{(i)}Z_n^{(i)}I_n^{(i)}(z) \qquad (3)$$

$$\frac{dI_n^{(i)}(z)}{dz} = -jk_{z,n}^{(i)}Y_n^{(i)}V_n^{(i)}(z) \qquad (4)$$

where $k_{z,n}^{(i)}$ is the propagation wavenumber and $Z_n^{(i)}(=1/Y_n^{(i)})$ is the characteristic impedance in the z direction. At the junction discontinuity, at z=0, the tangential fields components must be continuous, e.g.,

$$\sum_{n=0}^{\infty} V_n^{(3)}(0)\,\phi_n^{(3)}(x) = \begin{cases} \sum_{n=0}^{\infty} V_n^{(2)}(0)\cdot\phi_n^{(2)}(x), \text{ for } h_1 \le x \le h_3 \\ \sum_{n=0}^{\infty} V_n^{(1)}(0)\cdot\phi_n^{(1)}(x), \text{for } 0 \le x \le h_1 \end{cases} \qquad (5)$$

where h_1 and h_3 are the heights of the semi-infinite PPWG 1 and 3, respectively. Scalar-multiplying these equations with $\phi_m^{(3)}(x)$ and making use of the orthogonality relations, we obtained the two systems of equations and they may be written in the matrix form:

$$\underline{\mathbf{V}}_3 = \mathbf{R}^T\underline{\mathbf{V}}_1 + \mathbf{S}^T\underline{\mathbf{V}}_2 \qquad (6)$$

$$\underline{\mathbf{I}}_3 = \mathbf{R}^T\underline{\mathbf{I}}_1 + \mathbf{S}^T\underline{\mathbf{I}}_2 \qquad (7)$$

in which the elements of matrices **R** and **S** are the overlap integrals between the two sets of PPWG mode functions.

It is noted that the superscript T over a matrix signifies "transpose" of the matrix. $\underline{\mathbf{V}}_i$ and $\underline{\mathbf{I}}_i$ are the voltage and current vectors in each region, with $V_n^{(i)}(0)$ and $I_n^{(i)}(0)$ as their n^{th} element, respectively. The matrices **R** and **S** are responsible for the coupling among modes in region 1 and 3, and region 2 and 3, respectively, and will be referred to as the coupling matrices.

Scalar-multiplying (5) with $\phi_m^{(1)}(x)$ and making use of the orthogonality relations and expressing them in the matrix form as described above, we have

$$\underline{\mathbf{V}}_1 = \mathbf{R}\underline{\mathbf{V}}_3 \qquad (8)$$

similarly, scalar-multiplying (5) with $\phi_m^{(2)}(x)$ and making use of the orthogonality relations and expressing them in the matrix form as described above, we have

$$\underline{\mathbf{V}}_2 = \mathbf{S}\underline{\mathbf{V}}_3 \qquad (9)$$

Substituting of (8) and (9) into (6), we have the unitary condition:

$$\mathbf{R^TR} + \mathbf{S^TS} = \mathbf{1} \qquad (10)$$

where **1** is the identity matrix. It is noted that all the matrices and vectors are infinite in order. In practice, the matrices have to be truncated to a finite order for an approximate analysis. The order of truncation is equal to the number of modes retained in the approximate analysis. In general, (10) may be considered as an indicator to see whether the number of modes retained is sufficient.

Returning to Fig. 2, a set of PPWG modes is incident from region 1 while regions 2 and 3 are terminated. In general, the voltage and current vectors for TM modes in regions 2 and 3, at z=0, satisfy the following equations:

$$\underline{\mathbf{I}}_3(\mathbf{0}) = \mathbf{Y}_3^{(in)}\underline{\mathbf{V}}_3(\mathbf{0}) \qquad (11)$$

$$\underline{\mathbf{I}}_2(\mathbf{0}) = \mathbf{Y}_2^{(in)}\underline{\mathbf{V}}_2(\mathbf{0}) \qquad (12)$$

where $\mathbf{Y}_i^{(in)}$ is the input admittance matrix of the i^{th} region. Substituting of (11) and (12) into (6) and (7), and making use of the unitary condition (14), we could obtain, after some matrix operations, the following equations:

$$\underline{\mathbf{V}}_3(\mathbf{0}) = \mathbf{T}_{31}\underline{\mathbf{V}}_1(\mathbf{0}) \qquad (13)$$

$$\underline{\mathbf{I}}_1(\mathbf{0}) = \mathbf{Y}_1^{(in)}\underline{\mathbf{V}}_1(\mathbf{0}) \qquad (14)$$

where $\mathbf{Y}_1^{(in)}$ is the input admittance matrix of the overall structure. T_{31} is the voltage transformation matrix from ppwg 1 to ppwg 3 at the discontinuity. Up to now, the input-output relation of a bifurcated PPWG have been well developed, once the incident PPWG modes are given, the mode amplitudes, which contains TEM and higher-order modes, in each constituent region can be obtained.

3.2 Input-output of a sub-cell

As described in Section 2, the structure of a Tri-Plate with fins could be considered as the cascade of basic sub-cells, each of which consists of a bifurcated PPWG and PPWG of finite length. Since the structure is assumed to be symmetric, we could bisect the original structure into two half-structure; one is terminated by a perfect electric conductor (PEC) and the other is terminated by a perfect magnetic conductor (PMC).

It is necessary to determine the reflection of PPWG modes by the overall structure looking to the right at z=0. Moreover, once the reflected mode amplitudes are determined, it is straightforward to determine the electric and magnetic fields in the overall structure. For the reflection of PPWG modes incident from the left in Fig. 1, it is sufficient to have available an input admittance characterization at $z=0^-$, to take into account the effects of the cascaded sub-cells with the termination of a uniform PPWG. The input admittance matrix could be easily evaluated by making use of (14) and this constituted the building-block approach. The input-output relations of the sub-cells are evaluated successively from the output end of the uniform PPWG to the input end of the bifurcated PPWG. Thus, we have available the input admittance matrix denoted by $\mathbf{Y}_1^{(in)}$.

Returning to the input PPWG, at z=0, the voltage and current vectors are given by

$$\underline{\mathbf{V}}_1 = \underline{\mathbf{a}} + \underline{\mathbf{b}} \quad (15)$$

$$\underline{\mathbf{I}}_1 = \mathbf{Y}_1^{(o)}(\underline{\mathbf{a}} - \underline{\mathbf{b}}) \quad (16)$$

where $\mathbf{Y}_1^{(o)}$ is the characteristic admittance matrix in PPWG 1, $\underline{\mathbf{a}}$ and $\underline{\mathbf{b}}$ are incident- and reflected- voltage vectors, respectively. Since the voltage and current of the input PPWG 1 are related by $\mathbf{Y}_1^{(in)}$, we have the relationship between incident and reflected mode amplitudes:

$$\underline{\mathbf{b}} = \mathbf{\Gamma}\underline{\mathbf{a}}, \quad (17)$$

$$\mathbf{\Gamma} = (\mathbf{Y}_1^{(c)} + \mathbf{Y}_1^{(in)})^{-1}(\mathbf{Y}_1^{(c)} - \mathbf{Y}_1^{(in)}) \quad (18)$$

where $\mathbf{\Gamma}$ is the reflection matrix at z=0 in the PPWG 1.

Limited by the computer capacity, all the infinite summation and matrix dimension derived in the previous sections must be truncated to finite ones. The number of modes in each PPWG regions must be chosen correctly. Otherwise, the ensuring results may be wrong, even though they converge at all. This is known as the problems of relative convergence in the literature. In this paper, we choose the number of modes in each PPWG region in propotion to relative height of the waveguide.

4. Numerical Results and discussion

In this paper, we have proposed the novel transition structure of Tri-Plate with fins to examine the reflection to the source and field uniformity in the uniform region of a Tri-Plate. We have checked the reflection of non-uniform PPWG with the linear and hyper-tangent transition. Comparing with the commonly used transition structure, the novel ones offer a low return loss and maintain a uniform electric field behind the transition region.

For the field uniformity in the uniform region, the heights of uniform PPWGs are limited, such that only the TEM mode is supported. In the numerical analysis, the heights of uniform PPWGs at two ends of the transition waveguide are set to be 1cm and 15cm, respectively. We make use of the staircase approximation to simulate the commonly used structure. However, the step discontinuity herein may be considered as the degenerate case where the length of PPWG 2 as shown in Fig. 2 shrinks to zero.

To ensure the accuracy of the numerical results, we have checked the convergence of reflected power for different number of modes in the incident PPWG. At the same time, the field continuity across the interface between the transition and uniform regions have also verified carefully and obtain a good agreement with the tangential electric fields across the discontinuity.

In Fig. 3, we have a linear transition structure shown as a reference. To see the transition characteristics of the novel structure, we take the heights of steps and the fin length as variables and make use of the optimization algorithm to minimize the reflected power over the frequency range, in which only the TEM mode is propagating and all the higher modes are below-cutoff. Through the optimization process, we obtain the fin length of each step, as that the reflected power is smaller than that of the linear transition case, especially in the high frequency range.

To see the field uniformity of the novel structure, we plot the electric field distribution over the uniform PPWG region for the linear transition structure, as shown in Fig. 4, and that of the novel structure, as shown in Fig. 5. It is obvious that the novel structure has excellent uniformity compared with that of commonly used structure.

5. Conclusion

We have presented a novel structure, Tri-Plate with fins, for the improvement of the performance of Tri-Plates. Through the optimal selection of the structural parameters, it can achieve the low return-loss and maintain a uniform electric field on the transverse plane in the uniform region. Indeed, this offers a new technique for the design of practical Tri-Plates.

References

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Acknowledges

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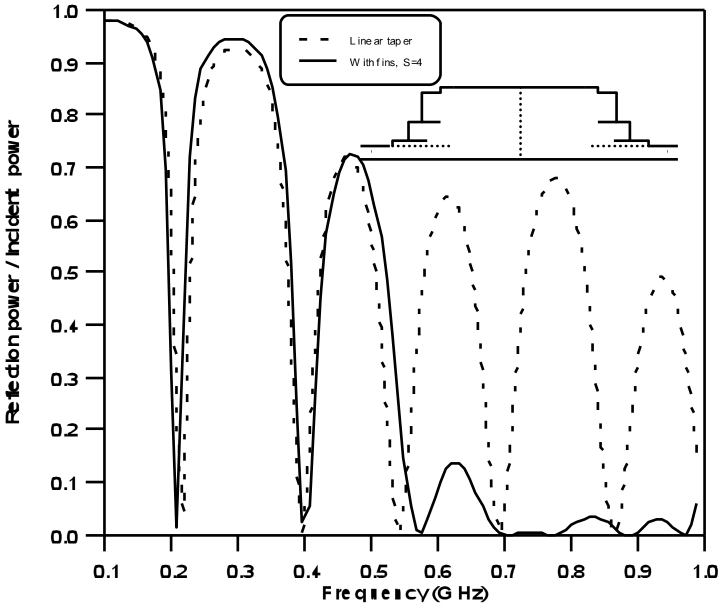

Fig. 3

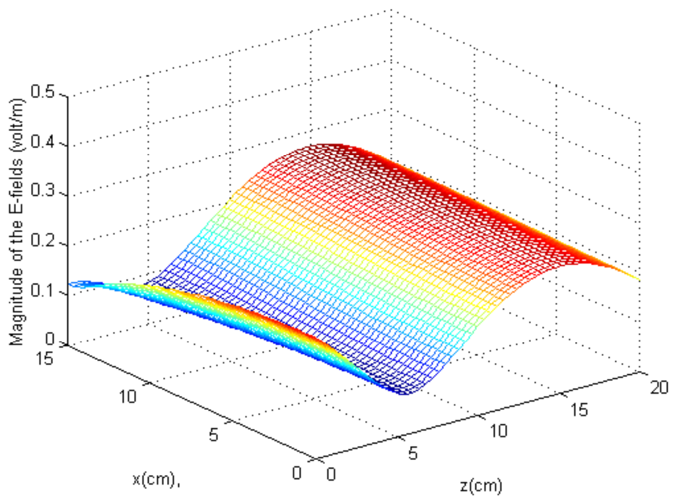

Fig. 4

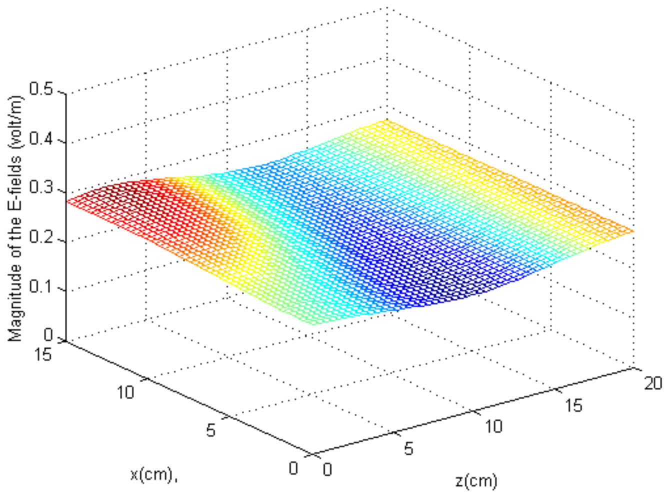

Fig. 5