CALCULATION OF RADIATION FROM MMIC ELEMENTS USING RADIATION MODE EXPANSION FORMULATION COMBINED WITH FD-TD ANALYSIS

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Abstract The authors have presented a new method based on radiation mode expansion theory combined with FD-TD technique for calculating transmitted, reflected and radiated fields from MMIC elements. Theoretical background and calculation procedures of this method have been explained thus far. However the numerical verification has not been made sufficiently. This paper verifies first the feasibility of this method and checks its accuracy by comparing numerical results with those of the past literature for MMIC open ends and right-angled bends. Radiation characteristics of these elements are next investigated from the viewpoint of radiation pattern as well as total radiated power.

I. INTRODUCTION

In microwave and millimeter wave integrated circuits, and monolithic integrated circuits, various circuit elements are often closely placed to each other, interconnected by microstrip-type lines. Therefore, it is very important to evaluate the amount of radiated fields as well as transmitted and reflected fields from each element [1]. The source fields of outgoing waves (reflected, transmitted and radiated waves) are obtained once the near fields around each element are calculated. This calculation is rather easily performed by invoking, for example, the FD-TD method [2], [3]. However, calculation of radiated waves is usually not so easy. Thus far, therefore, radiated fields have been calculated using mostly the Moment Method (MM) [4], [5]. In this MM formulation, however, Green's functions of very complicated form must be used and moreover the region where unknown sources distribute extends infinitely in theory.

The authors have presented a new numerical and analytical approach for calculating fields reflected, transmitted, and radiated from MMIC elements. These fields are calculated from the sources on a "finite" sized closed surface; Green's functions are not needed [6], [7]. The essential features of the method is to establish pertinent three-dimensional modes, in terms of which outgoing waves can be expanded, and the expansion coefficients of which can be obtained by taking their reaction with the source fields. As for the reflected and transmitted fields, those modes are nothing but guided modes of straight lines, and field distributions and propagation constants of these modes are easily calculable by utilizing, usually, numerical methods such as the FD-TD method. This mode concept is extended in the present method to radiation modes, which are very conveniently used for expressing radiated fields.

This method was first applied to microstrip patch antennas with an "infinite" ground plane [6] to calculate radiated fields in the half-space. Then it was found that this method is much more useful when applied to the problems of MMIC elements because radiation modes are rigorously defined when the substrate extends infinitely and this situation applies practically to the case of MMIC. Thus, the theory was extended to the problem of calculating reflected, transmitted and radiated fields from MMIC elements and typical numerical examples were also shown [7]. However, the validity and accuracy have not been checked sufficiently. This paper solves this important problem by comparing the results of numerical calculation for MMIC open ends and right-angled bends with those of the past work, accomplishing reasonable validity and accuracy check. In addition to this, the paper investigates numerically the radiation characteristics of open ends and right-angled bends. Dependence of total radiated power and radiation patterns on strip width and dielectric constant is also discussed here.

II. SUMMARY OF THE METHOD

The microstrip line bend configuration of Fig.1 is used here for explanation of the present method. The method can be divided into three major procedures. First one is the calculation of field distribution and propagation constant of the guided mode propagated in the straight microstrip line. This guided mode is used not only as the incident mode in the second procedure but also as the incident, reflected and transmitted guided modes in the third procedure. Second procedure is the calculation of field distribution around the discontinuities inside the region bounded, for example, by the surface S_C in Fig.1. The last procedure is the calculation of fields transmitted, reflected, and radiated from the discontinuities. In this procedure, only the field distribution on the closed surface S_0 chosen inside S_C is used to take reaction with the corresponding modes. The FD-TD method is invoked for

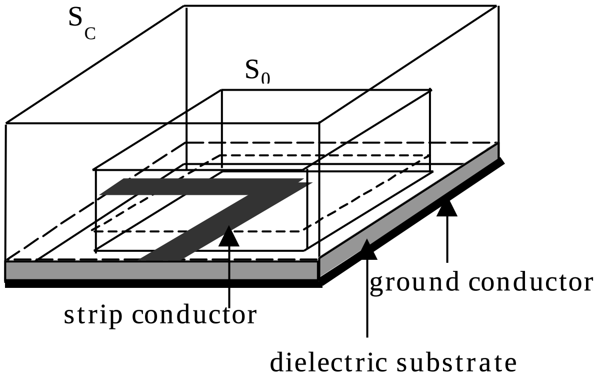


Fig.1. Typical microstrip line discontinuity.

the first and second procedures, while the theory of radiation mode expansion [6],[7] is applied to the last procedure, which is the most important portion of the whole process of the method.

Radiation modes are defined for the half-space region shown in Fig.2. Their functional expressions are, for spectrum p, written as

$$\mathbf{E}_p = \mathbf{e}_p \, e^{-j\beta_p x} \tag{1}$$

$$\mathbf{H}_p = \mathbf{h}_p \, e^{-j\beta_p x} \tag{2}$$

$$\mathbf{e}_p = \tilde{\mathbf{e}}_p e^{-j\alpha_p y}, \quad \mathbf{h}_p = \tilde{\mathbf{h}}_p e^{-j\alpha_p y} \tag{3}$$

The explicit expressions of $\tilde{\mathbf{e}}_p$ and $\tilde{\mathbf{h}}_p$ are derived, as usual, using the solution of wave equation, together with boundary conditions at the dielectric-air interface and the conductor surface, as well as the orthogonality properties of the modes in the yz plane [6], [7].

The radiated fields ($\mathbf{E}^r$, $\mathbf{H}^r$) in the half space of z $\geq$ 0 can be expanded in terms of the radiation mode fields, for example, as

$$\mathbf{E}^{r(+)} = \int_{-\infty}^{\infty} d\alpha_p e^{-j\alpha_p y} \sum_{\nu=e,h} \Big(\Big\{ \sum_m a_m^{\nu(+)} \tilde{\mathbf{e}}_m^{\nu(+)} + \int_0^{\infty} d\gamma_0 b^{\nu(+)} \tilde{\mathbf{e}}^{\nu(+)}(\gamma_0) \Big\} e^{-j\beta_p x} \Big) \tag{4}$$

where

$$\gamma_0^2 = k_0^2 - \xi_0^2 , \qquad \xi_0^2 = \alpha_p^2 + \beta_p^2 \tag{5}$$

The superscript (+) means the region x$\geq$ 0. This sign is replaced by (—) for the region x $\leq$ 0, for which β_p is replaced by $-\beta_p$. The superscript ν takes e, which means E type mode, or h, which means H type mode, where E type and H type modes mean the modes without Hz and Ez, respectively.

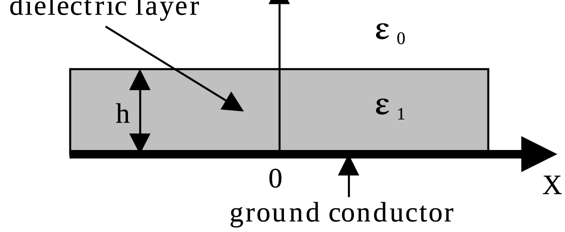


Fig.2. Half-space partitioned by a typical substrate structure.

The summation over m represents the

sum of substrate modes and the term of γ_0-integral represents the spectral sum of space modes. Here, substrate modes are those with the discrete wave number spectrum in the z direction, which corresponds to the fields propagating along the dielectric layer, while space modes are those with the continuous wave number spectrum in the z direction, which corresponds to the fields propagating in the air region. The magnetic field is also expressed similarly. The expansion coefficients $a_m^{\nu(\pm)}$ and $b^{\nu(\pm)}$ are determined using orthonormality properties pre-defined and Lorentz reciprocity theorem, once the source distribution is given, for example, on S_0 in Fig.1. Total radiation field is the sum of the radiated field into the air region, P_{spa}, and that into the substrate region, P_{sub}, which are calculated, respectively, from

$$P_{spa} = \int_{-k_0}^{k_0} d\alpha_p \int_0^{\sqrt{k_p^2-\alpha_p^2}} d\gamma_0 \cdot \sum_{g=+,-} \left(|b^{e(g)}|^2 + |b^{h(g)}|^2 \right) \quad (6)$$

$$P_{sub} = \sum_{g=+,-} \sum_m \left(\int_{-\xi_{0m}^e}^{\xi_{0m}^e} |a_m^{e(g)}|^2 + \int_{-\xi_{0m}^h}^{\xi_{0m}^h} |a_m^{h(g)}|^2 \right) d\alpha_p \quad (7)$$

Incidence, reflection and transmission coefficients of the guided mode, a_0, a_r, a_t, are calculated from

$$a_0 = -\frac{1}{4}\int_{S_1} \left(\mathbf{E}_i^* \times \mathbf{H}_1 + \mathbf{E}_1 \times \mathbf{H}_i^* \right) \cdot \mathbf{i}_n \, ds \quad (8)$$

$$a_r = \frac{1}{4}\int_{S_1} \left(\mathbf{E}_i^* \times \mathbf{H}_1 + \mathbf{E}_1 \times \mathbf{H}_i^* \right) \cdot \mathbf{i}_n \, ds \quad (9)$$

$$a_t = -\frac{1}{4}\int_{S_2} \left(\mathbf{E}_i^* \times \mathbf{H}_2 + \mathbf{E}_2 \times \mathbf{H}_i^* \right) \cdot \mathbf{i}_n \, ds \quad (10)$$

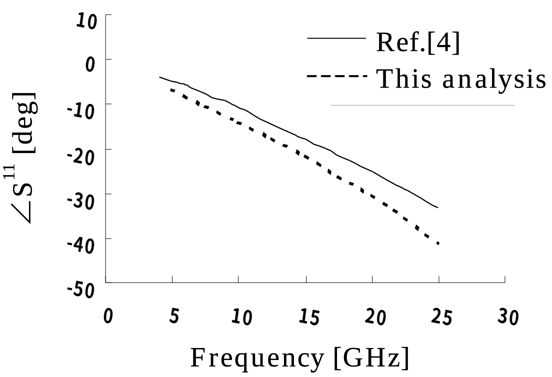


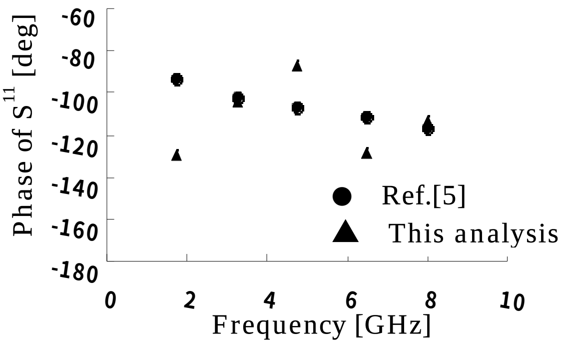
Fig.3. Phase of S_{11}

where S_1 and S_2 are the plane transverse to the microstrip line of the input side and the output side, respectively, $(\mathbf{E}_1, \mathbf{H}_1)$ and $(\mathbf{E}_2, \mathbf{H}_2)$ are the fields on S_1 and S_2 respectively, and $(\mathbf{E}_i, \mathbf{H}_i)$ are the incident mode fields.

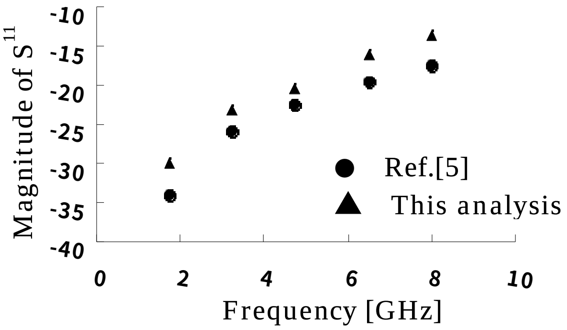
III. NUMERICAL EXAMPLES

Figure 3 shows the phase of S_{11} for the open end of strip width w=0.6033mm, substrate thickness h=0.635mm, and substrate relative dielectric constant ε_r=9.9. Comparison is made with the results obtained by Moment Method [5]. Phase and amplitude of S_{21} are also compared with the results of Ref.[5] for the right-angled bend of w=2.4mm, h=0.787mm, and ε_r=2.2, which is shown in Fig.4, where the distances of input and output ports from the bend inner corner, L_1 and L_2, are chosen here as L_1=L_2=66.7mm although the values are written in Ref.[5] to be 55.2mm, because it was concluded from detailed examination that 55.2mm is not correct and that the results agree well with those of Ref.[5] when the value is set to be 66.7mm. Other examples are also studied to compare the results with those of the past literature, although pertinent references can be found very few. One of the advantages of the present method is to be able to check the accuracy from the viewpoint of energy conservation such that incident guided mode power must be equal to the sum of reflected and transmitted guided mode power, and radiated power in the space and substrate regions. This energy conservation error is checked in the numerical examples treated here. The characteristics of radiation patterns are investigated in detail for open ends and right-angled bends for various values of strip width and substrate dielectric constant, with the characteristic impedance being kept as 50Ω in all cases. It is found that total radiated power increases generally as the strip width or substrate dielectric constant decreases. Two typical examples of radiation pattern in the xy plane, i.e., substrate plane, for the bend shown in

Fig.5 with the coordinates are presented in Fig.6; (a) is for w=1.92mm and h=0.630mm and (b) is for w=2.64mm and h=0.866mm, both with ε_r=2.2 and f=8GHz.



(a) Phase



(b) Amplitude

Fig.4. S_{21} for right-angled bend.

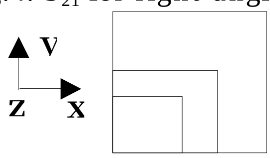


Fig.5. Bend and the coordinates.

IV. CONCLUSION

Results of validity and accuracy check were presented of the new method of using radiation mode expansion theory together with the FD-TD technique.

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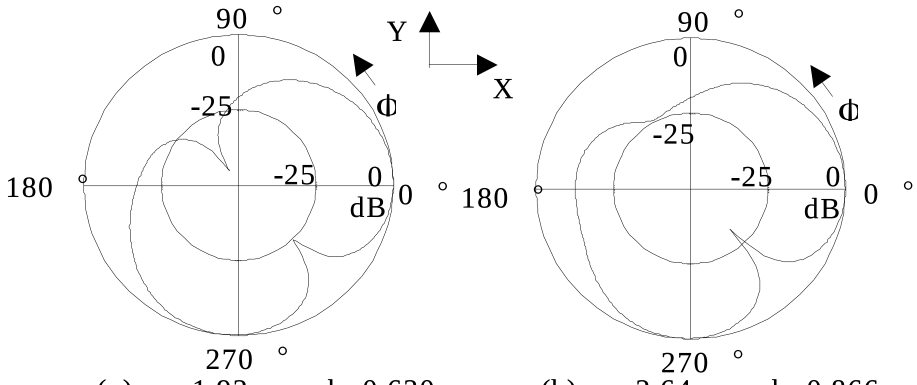

(a) w=1.92mm, h=0.630mm (b) w=2.64mm, h=0.866m

Fig.6. Radiation patterns in the xy plane(ε_r=2.2, f=8GHz).