Mutual Coupling Between Microstrips Through a Printed Aperture of Arbitrary Shape in Multilayered Media

Chinglung Chen, Ming-Ju Tsai, and Nicolaos G. Alexopoulos

Abstract— **A concise formulation of mixed-potential integral equation (MPIE) is developed to account for the mutual coupling effects between electric and magnetic current sources in a multilayered medium. Unlike the electric field integral equation (EFIE) or magnetic field integral equation (MFIE), this expression only requires the less singular vector potential to evaluate the mutual impedance integral. As a result, computational speed and accuracy are enhanced. In addition, this formulation provides a physical insight of how this mutual coupling occurs. Although the odd symmetry of the impedance matrix concluded from reciprocity theorem is not obvious, it is numerically evaluated and justified. Finally, a vertical transition between back-to-back microstrip lines is calculated and compared with published data. Bandwidth improvement of this transition is also demonstrated by introducing a bowtie slot for the vertical coupling.**

I. Introduction

PRINTED distributed apertures [1] play an important role in microwave and millimeter-wave electronics. For example, coplanar waveguide and slotline are popularly used in microwave and millimeter-wave integrated circuits (MMIC's). In addition, aperture coupling is widely applied in microwave circuits in multilayered media as for a vertical transition [2]–[4] or as in directional coupler applications [5]. With the increase in complexity and requirements in microwave circuit and antenna design, the use of microstrips, slotlines, and coplanar waveguides together in a single module is unavoidable. In order to achieve an optimal design of a microwave circuit system, a mixed-potential integral equation (MPIE)-based moment method [6], [7] is developed to investigate the self and mutual coupling among microstrips and printed apertures.

Mutual coupling between the same kind of current sources (e.g., electric versus electric or magnetic versus magnetic) has been investigated and well formulated in spatial domain [6], [7]. However, this phenomenon has not yet been intensively discussed between different kinds of current sources because of its complexity in the spatial domain formulation [8]–[10]. It is found here that a concise expression can be obtained to evaluate this mutual coupling behavior. Its simplicity can lead to a great enhancement of computational efficiency compared with the formulation based on electric field integral equation (EFIE) and magnetic field integral equation (MFIE) [8]. A vectorized triangular basis function [6] is chosen as the basis and testing function for the implementation of the Galerkin method. Due to its arbitrarily defined shape and vector nature, which supports the expansion of transverse and longitudinal current components, this basis function is well suited to simulate an arbitrarily oriented current distribution within any arbitrarily shaped microstrip or aperture. With these features, this MPIE formulation can be implemented to investigate a microwave integrated circuit and antenna system consisting of arbitrarily shaped microstrips and printed apertures within a multilayered medium and provide good computational efficiency.

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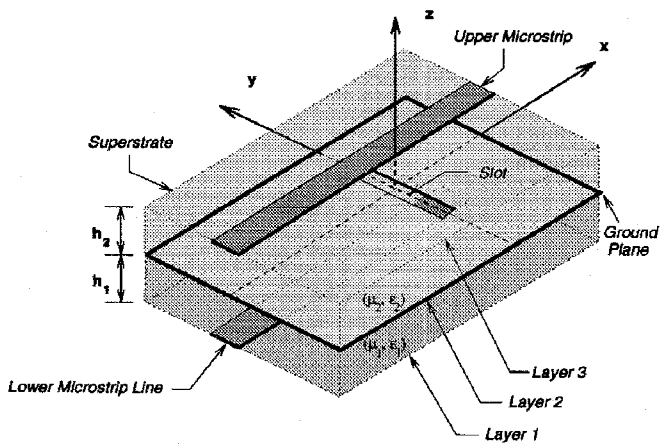

Fig. 1. Structure of a microstrip-line-fed aperture coupled microstrip.

II. Modeling of the Problem

A typical structure of interest is shown in Fig. 1. The electric current $\vec{J}_1$ on the lower microstrip line, the tangential electric field $\vec{E}_2$ in the aperture, and the electric current $\vec{J}_3$ on the upper microstrip are modeled with subdomain basis functions. An application of the equivalence principle allows the aperture to be closed and replaced with a fictitious magnetic current $\vec{M}_2 = \hat{z} \times \vec{E}_2$ below the common ground plane and $-\vec{M}_2$ above the common ground plane. As a result, our original problem has been divided into two isolated problems, namely

Region L: Below the common ground plane $(-(h_0 + h_1) < z < 0)$.

Region U: Above the common ground plane $(z > 0)$.

These are connected by matching the tangential magnetic fields across the aperture.

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A. Modeling Implementation

To rigorously solve this problem, we model the total fields in each region first. Boundary conditions on the microstrips and aperture are then enforced to construct the mixed-potential integral equations. Galerkin's method is applied to solve the electric and magnetic current distributions on the microstrips and aperture. A vectorized triangular basis function [6] is found to be a good choice because its shape can be arbitrarily defined. We then expand the electric and magnetic current distributions as

$$\vec{J}_1 = \sum_{n=1}^{N_1} A_n \vec{f}_{n1}, \qquad \vec{M}_2 = \sum_{n=1}^{N_2} B_n \vec{f}_{n2}, \qquad \vec{J}_3 = \sum_{n=1}^{N_3} C_n \vec{f}_{n3} \tag{1}$$

where $\vec{f}_{n1}$, $\vec{f}_{n2}$, and $\vec{f}_{n3}$ are arbitrarily defined triangular basis functions located in layers 1, 2, and 3, respectively. Upon introducing these distribution functions into the mixed-potential integral equations (1)–(3) and testing them with $\vec{f}_{m1}$, $\vec{f}_{m2}$, and $\vec{f}_{m3}$, a system of linear equations will be obtained as

$$\begin{bmatrix} [\vec{E}_{\text{inc}}, \vec{f}_{m1}] \\ [\triangle\vec{H}_{\text{inc}}, \vec{f}_{m2}] \\ [0] \end{bmatrix} = \begin{bmatrix} [Z_{11}] & [W_{12}] & [0] \\ [U_{21}] & [Y_{22}] & [U_{23}] \\ [0] & [W_{32}] & [Z_{33}] \end{bmatrix} \cdot \begin{bmatrix} [A] \\ [B] \\ [C] \end{bmatrix} \tag{2}$$

where $[Z_{ii}]$, $[W_{ij}]$, $[U_{ji}]$, and $[Y_{jj}]$ are self- and mutual-coupling integral submatrices between two basis functions located at $z = -h_1$, $z = 0$, or $z = h_2$, respectively $(i, j \in 1, 2, 3)$. $[A]$, $[B]$, and $[C]$ are unknown coefficient vectors of basis functions on the microstrips and aperture, respectively.

B. Self- and Mutual-Coupling Model

The formulas for the self-coupling submatrices have been derived completely in [6] and [7]. The major difference of the MPIE applied here is the formulation of the mutual coupling between electric and magnetic currents as

$$W^{mn}_{(1,3)2} \equiv \frac{1}{\epsilon_{(1,2)}\epsilon_0} \times \left\{ \begin{array}{l} \int_{C^{\pm}_{(1,3)m}} \vec{F}^{(L,U)}_{mn,(1,3)2,z} \cdot [\vec{f}_{m(1,3)} \times \hat{u}_m] dc_{(1,3)} \\ + \int_{\Gamma^{\pm}_{(1,3)m}} \left[\frac{\partial}{\partial z}\vec{F}^{(L,U)}_{mn,(1,3)2,t} \times \vec{f}_{m(1,3)}\right] \cdot \hat{z} ds_{(1,3)} \end{array} \right\} \tag{3}$$

$$U^{mn}_{2(1,3)} \equiv \frac{-1}{\mu_{(1,2)}\mu_0} \times \left\{ \begin{array}{l} \int_{C^{\pm}_{2m}} \vec{A}^{(L,U)}_{mn,2(1,3),z} \cdot [\vec{f}_{m2} \times \hat{u}_m] dc_2 \\ + \int_{\Gamma^{\pm}_{2m}} \left[\frac{\partial}{\partial z}\vec{A}^{(L,U)}_{mn,2(1,3),t} \times \vec{f}_{m2}\right] \cdot \hat{z} ds_2 \end{array} \right\} \tag{4}$$

where $\vec{F}^{(L,U)}_{mn,(1,3)2}$ and $\vec{A}^{(L,U)}_{mn,2(1,3)}$ are the vector potential distribution functions within the testing region $((x, y) \in \vec{f}_{m(1,2,3)})$, which is generated by the electric and magnetic current basis function $\vec{f}_{n(1,2,3)}$, respectively. C_m and Γ_m are the contour and area of the basis function $\vec{f}_m$.

From (3) and (4), the physical mechanism of the mutual coupling between electric and magnetic currents can be observed. If the medium is homogeneous, the vector potential component in vertical direction will disappear. In this case, the impedance matrix is only contributed to by a cross product between potential and testing functions (such as a stripline fed slot [9], [10]). Since this vector potential component points to the same direction as the basis function, it means that it will couple more electromagnetic energy transversely rather than collinearly. As the multilayered substrate is introduced, the vertical-directional vector potential starts to contribute. The mutual coupling behavior will be discussed further in the next section by applying these formulations into a real example.

Compared to the work done by EFIE and MFIE [8], the formulas shown here only require two Green's functions of vector potential with less singular property and easy implementation features. In contrast to the highly singular Green's function of electric field and its complexity for applications, the same accuracy is obtained here with reduced numerical effort. For example, a microstrip line fed aperture-coupled patch antenna with about 1000 cells can be solved within 5-min CPU time on a IBM RISC 6000 machine, with more than half of the time being spent on matrix inversion subroutine for each frequency. Furthermore, the smaller the distance between the microstrip and slot, the more accuracy is secured because of the less singular Green's functions of the vector potential.

III. Results

From reciprocity theorem, the cross-coupling terms ($[W^{mn}_{(1,3)2}]$ and $[U^{nm}_{2(1,3)}]$) are expected to be odd-symmetrical. However, this cannot be concluded from (3) and (4) directly. As a result, a numerical experiment is implemented to justify this property. The mutual coupling between microstrip and slot consisting of 15 basis functions with the same dimension and position in a single-layered substrate is calculated and shown in Fig. 2. It is observed that the mutual impedance is almost identical except for the minus sign difference, which accounts for the odd symmetry as expected. In addition, weak coupling is observed between the first basis function over the microstrip and slot even though the radial distance (ρ_{11}) is zero. On the first basis on the microstrip, the mutual coupling from the odd-numbered basis on the slot is much less than that from the even-numbered basis. These phenomena can be explained because the mutual coupling between two collinear basis functions on microstrip and aperture is limited, due to the cross-product between potential and basis functions in (3) and (4). Here, the odd-numbered basis over the slot is oriented along the same direction as the first basis on the microstrip, while the even-numbered basis is not.

After the odd symmetry is tested, this MPIE formulation is applied to microwave circuit-element design. An aperture coupled two-port back-to-back microstrip lines are investigated here and the result is shown in Fig. 3. Comparison with published results in [4] shows agreement within 0.1 GHz for data under 15 GHz. For the slight deviation in high-frequency band, it can be concluded that two cells in transverse direction, as adopted in [4], are not enough to accurately model the

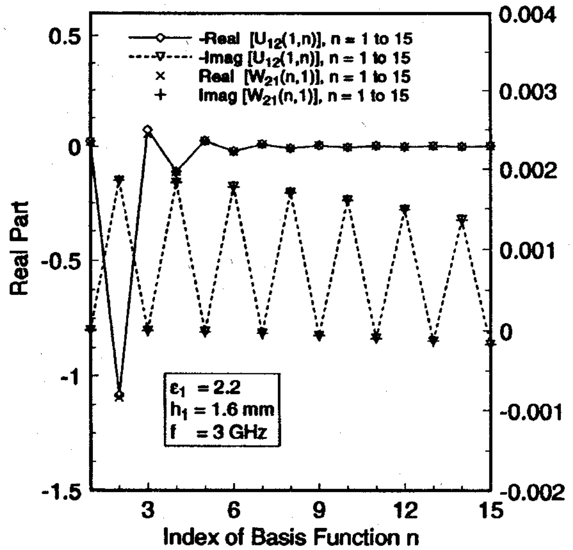

Fig. 2. Comparison of the mutual impedance between microstrip and slot in a single-layered substrate.

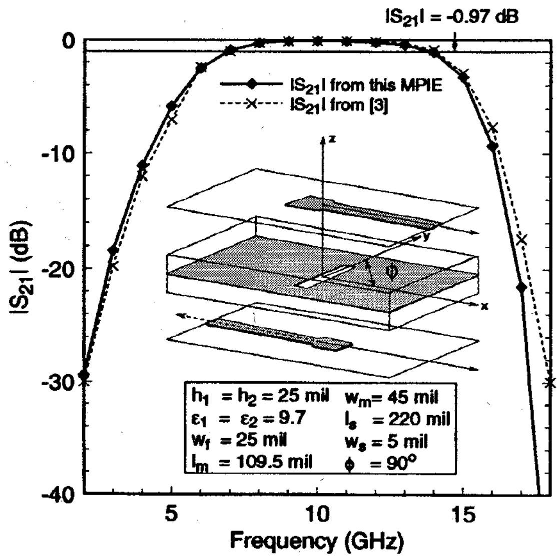

Fig. 3. Comparison of S_{21} for a back-to-back two-port microstrip line transition (w_f: Microstrip line width, l_m: Open stub length, w_m: Open stub width, l_s: Slot length, w_s: Slot width).

microstrip line. We use three cells in microstrip line and seven cells in the open stub to model it more precisely. On the other hand, two cells are enough to give accurate simulation data for low frequencies. As a result, the coincidence and discrepancy are all expected. Having demonstrated the accuracy of our method, next a bowtie slot is used to enhance the transition bandwidth. This increase in bandwidth is shown in Fig. 4.

IV. Conclusion

In this letter, a concise formulation of MPIE which accounts for the mutual coupling between electric and magnetic currents in multilayered structure is developed. It provides physical insight and computational efficiency by introducing a vector potential approach. Finally, this formulation is successfully

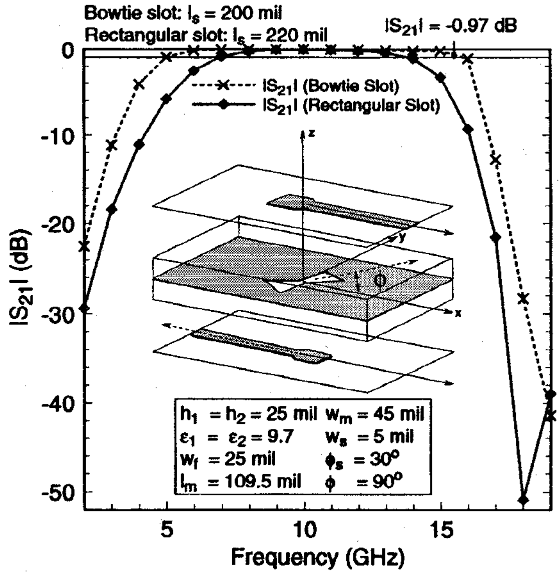

Fig. 4. Comparison of S_{21} between rectangular slot and bowtie slot coupled back-to-back two-port microstrip line transition (w_f: Microstrip line width, l_m: Open stub length, w_m: Open stub width, l_s: Slot length, w_s: Slot width at $y = 0$, ϕ_s: Bowtie arc angle).

implemented to analyze a back-to-back two-port microstrip line transition. It is proved to be extendible into an optimal design of a microwave antenna and circuit system containing arbitrarily shaped microstrips, coplanar waveguides, and printed apertures.

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