OPTIMIZATION OF APERTURE TRANSITIONS FOR MULTI-PORT MICROSTRIP CIRCUITS

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ABSTRACT

The printed aperture of arbitrary shape is introduced into multi-port microstrip circuits as a vertical transition within a multi-layered structure. Its use proves to be practical in the design as well as manufacturing process of multi-layered circuits. With the help of the mixed-potential integral equation based moment method, it becomes possible to analyze and optimize the performance of this arbitrary shape aperture transition for multi-port circuit applications. Bandwidth enhancement is obtained by changing the shape of the slot for a two-port back-to-back microstrip transition. Minimized size and mutual coupling have been thoroughly studied for optimized circuit performance. Using this transition, a 3-port power divider with -3 dB amplitude and 180 degree phase difference and a 4-port 3 dB directional coupler have been designed.

I. INTRODUCTION

Aperture coupling has been widely utilized in microwave circuits within multi-layered media as a vertical transition [1]-[5] as well as directional coupler applications [6]-[7]. In addition, coplanar waveguide and slotline are popularly used in microwave and millimeter-wave integrated circuits (MMIC's). With the increase in complexity and requirements in microwave circuit design, we develop a mixed-potential integral equation (MPIE) [8] based moment method in order to investigate the aperture coupling effect between microstrips in multi-layered media.

The application of printed aperture as a vertical transition has been investigated intensively [2]-[4]. Recently, Sercu [5] presented a spatial-domain integral equation approach to investigate this structure for a two-port. However, since most of the previous works are either based on simplified theory or rectangular shape basis function, the investigation of arbitrarily-shaped printed slot and its impact in optimization of bandwidth are beyond their scope. In this research, the bow-tie slot has been introduced successfully to enhance the transmission coefficient bandwidth coefficient by 50%. A simple change in slot orientation is used to achieve maximum coupling for two back-to-back microstrips with arbitrary crossing angle, which is realistic for practical microwave circuits. The mutual coupling between this transition and surrounding microstrip circuits is also investigated. With a reasonable spacing ($\geq \frac{\lambda_g}{4}$), it is observed that the mutual coupling effect can be neglected.

In addition to the study of two-port microstrip transition, same approach is extended to investigate multi-port microstrip transitions such as a three-port back-to-back microstrip power divider and four-port directional coupler by using two slots. It is shown that by introducing a quarter-wavelength step discontinuity over the upper microstrip line, a good return loss can be reached for a three-port power divider. The introduction of bow-tie slot also enhances the bandwidth substantially. Lastly, a directional coupler is established by properly adjusting the slot length of two slots with fixed separation distance. As a conclusion, this research provides the versatility to design a multi-port microstrip circuit with the use of a printed aperture.

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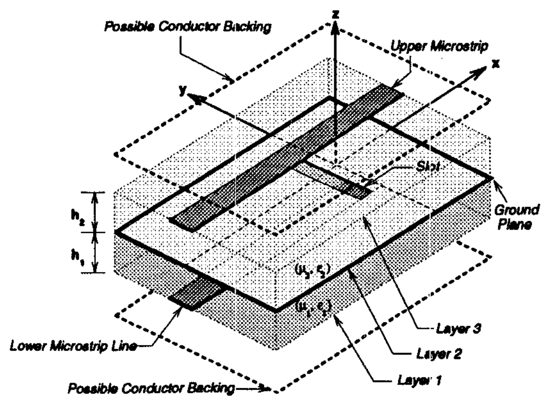

Figure 1: Structure of a Microstrip Line Fed Aperture Coupled Microstrip

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II. MODELING OF THE PROBLEM

A typical structure of interest is shown in Figure 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 triangular patch 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 upper ground plane and $-\vec{M}_2$ above the upper ground plane.

Galerkin's method is applied next to solve the mixed-potential integral equations [8] and acquire the electric and magnetic current distributions on the microstrips and aperture. A vectorized triangular basis function [9] is found to be a good choice because its shape can be arbitrarily defined. We then expand the electric and magnetic current distributions as:

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

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 and testing them with $\vec{f}_{m1}$, $\vec{f}_{m2}$, and $\vec{f}_{m3}$. A system of linear equations will be obtained as:

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

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. $\vec{E}_{inc}$ and $\Delta \vec{H}_{inc}$ are the incident electric and magnetic fields from the lower microstrip feed line. Once these current distributions are extracted, the scattering parameters will be calculated.

The formulas for the self-coupling submatrices have been derived completely in [9, 10]. The major difference of the MPIE applied here is the formulation of the mutual coupling between electric and magnetic currents [8]. This concise formulation not only provides good computational efficiency, it also gives physical insight of the coupling mechanism. We will discuss this further during the presentation.

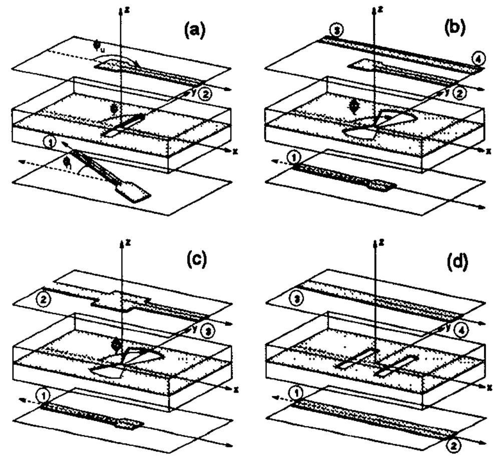

Figure 2: Application of Printed Slot into Multi-Layered Microwave Circuit. (a). Two-Port Slot-Coupled Microstrip Transition, (b). Two-Port Slot-Coupled Microstrip Transition with Adjacent Microstrip Circuit, (c). Three-Port Slot-Coupled Power Divider, (d). Four-Port Slot-Coupled Directional Coupler.

III. RESULTS

In multi-layered microwave integrated circuit applications , printed slots have proven to be versatile vertical transitions. They can be widely used to couple electromagnetic energy from one side of circuit module to another side which is backed by a perfect conductor. Some useful circuit applications under investigation is shown in Figure 2. First of all, aperture coupled two-port back-to-back microstrip lines are studied and the result is shown in Figure 3. By comparison with published results in [5], the agreement is within 0.1 GHz for data under 15 GHz. For the slight deviation in the high frequency band, it can be concluded that 2 cells in transverse direction as adopted in [5], are not enough to accurately model the microstrip line. We use 3 cells in microstrip line and 7 cells in the open stub to model it more precisely. On the other hand, two cells are sufficient to give accurate simulation data for low frequencies. As a result, the agreement and discrepancy are all expected. Having demonstrated the accuracy of this method, next a bow-tie slot is used to enhance the transition bandwidth. This bandwidth increase for the transmission coefficient can reach as high as 50% as shown in Figure 4. The larger the bow-tie arc angle is, the more enhancement in bandwidth is expected. In addition, its length is reduced compared with rectangular slot. In our research, the cross rectangular slot and cross bow-tie slot are also studied and produce similar improvement as shown here. As a result, properly adjusting the slot shape can lead to good coupling within a wider frequency range and

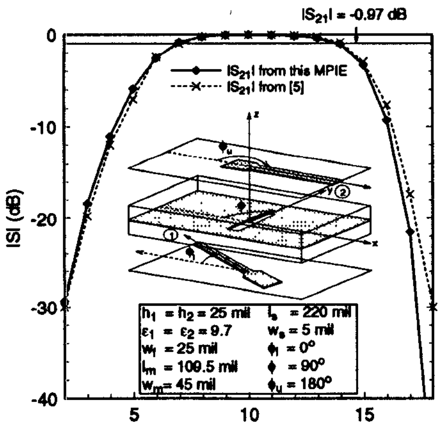

Figure 3: Comparison of S_{21} for A 2-Port Rectangular Slot-Coupled Microstrip Line Transition (w_f: Microstrip Line Width, l_m: Open Stub Length, w_m: Open Stub Width, l_s: Slot Length, w_s: Slot Width).

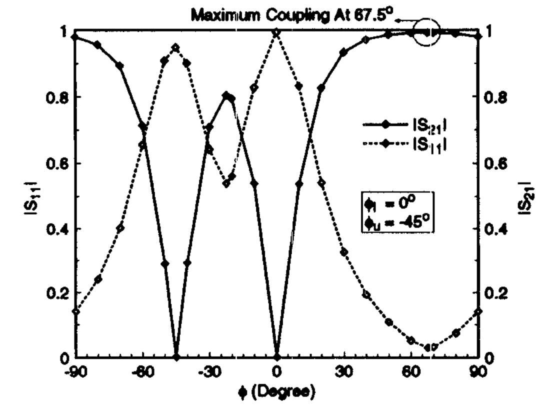

Figure 5: S Parameters v.s. Slot Orientation Angle for A 2-Port Rectangular Slot-Coupled Microstrip Transition With a 45° Crossing Angle (All the Geometrical and Material Parameters Are The Same As Figure 3).

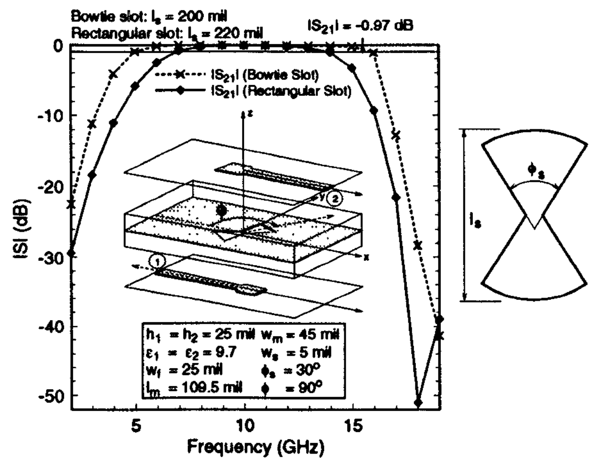

Figure 4: Comparison of S_{21} Between 2-Port Rectangular Slot and Bow-tie Slot-Coupled Microstrip Line Transition (w_f: Microstrip Line Width, l_m: Open Stub Length, w_m: Open Stub Width, l_s: Slot Length, w_s: Slot Width at $y = 0$, ϕ_s: Bow-tie Slot Arc Angle).

minimized longitudinal size, which is also critical in practical microwave circuit design.

In realistic design, the available space to put the coupling slot is limited because of the increased element density in a microwave circuit package. These two back-to-back microstrip lines also are not always oriented collinearly. In order to send the signal from one module to another, the aperture coupling between arbitrarily-crossed microstrip lines has to be properly modeled and optimized. In this research, the optimal slot location is carried out by using our full-wave MPIE technique. Numerical results are shown in Figure 5. It is observed that total transmission can be reached if the orientation angle of the slot is properly chosen. As a conclusion from our simulation results, a simple rule can be made to help in deciding this angle. This result will be presented in the symposium. Once the slot orientation angle is obtained, improvement in bandwidth and size minimization can be carried out by introducing the changing of slot shape as we did for collinearly-located microstrip lines. In addition, since the slot normally is more than a quarter wavelength long, the mutual coupling generated by the introduction of slot needs to be investigated as well. These factors will be intensively discussed during the presentation.

Lastly, two multi-port slot-coupled microstrip circuits are investigated as well. The first one is a three-port power divider consisting of a terminated microstrip, an infinitely-long microstrip line with step discontinuity and a single slot. From Figure 6, -3 dB equally divided signals with 180 degree phase difference appear on port 2 and 3 of the upper microstrip line. Introducing a bow-tie slot improves the -3 dB bandwidth by approximately 60%. During the investigation, it is observed that if the upper microstrip line is introduced without a step discontinuity, a high return loss will appear. Only after putting this quarter-wavelength step with proper width, a good return loss performance is obtained. Same conclusion of the slot orientation angle for two arbitrarily-crossed microstrip transition also applies here. It implies that this power divider can be optimized and to be incorporated into a microwave circuit package with no specification of location. In addition, another directional coupler con-

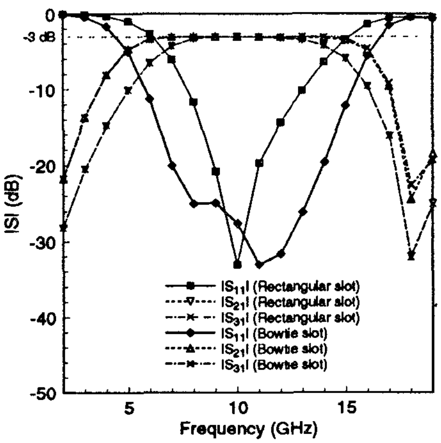

Figure 6: Comparison of the S Parameters Between Rectangular Slot-Coupled and Bow-tie Slot-Coupled 3-Port Double-Layered 3 dB Power Divider (All the Geometrical and Material Parameters Are the Same As Figure 3 and 4 Except: Upper Microstrip Step Length: 210 mil, Upper Microstrip Step Width: 47 mil, Rectangular Slot Length: 216 mil, Rectangular Slot Width: 5 mil, Bow-tie Slot Length: 200 mil, Bow-tie Slot Width At $y = 0$: 5 mil).

sisting of two rectangular slots separated by $\frac{\lambda_g}{8}$ has been studied. Good performance of return loss and isolation can be carried out with -3 dB transmission and coupling.

IV. CONCLUSIONS

In this paper, a concise formulation of MPIE which accounts for the mutual coupling between electric and magnetic currents in multi-layered structure is developed. It provides physical insight and computational efficiency with the introduction of the vector potential approach. Finally, this formulation is successfully implemented to analyze a multi-port aperture-coupled microstrip transition within multi-layered media. 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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