Scattering Analyses of Asymmetric Conductor-Backed CPW Open-End Discontinuity Problem

Shih-Ping Liu and Ching-Kuang C. Tzuang

Abstract—**The space-domain integral equation method using the generalized scattering matrix description of microwave passive circuits is employed to investigate the mode conversion of a CBCPW open-end discontinuity with unequal side plane widths. The conversion into two additional dominant modes, the c-mode-like mode and the π-mode-like mode, and into the transmitted microstrip mode from an incident CPW mode is studied against side plane width, degree of asymmetry, substrate thickness, and frequency. Theoretical results are in excellent agreement with experimental ones.**

I. Introduction

THIS WORK aims to analyze a benchmark element of important coplanar waveguide building blocks frequently applied in hybrid and monolithic microwave integrated circuits [1], with emphasis placed on the scattering analyses of the mode conversion inherently residing on these passive structures [2]–[9]. As seen in Fig. 1, a simple conductor-backed coplanar waveguide (CBCPW) open-end with two connected side planes of unequal widths is investigated to demonstrate important physical phenomena associated with this overmoded guided-wave structure. The asymmetry of the side planes is often encountered in practical circuits; its effect, however, is not clearly recognized so far. There are at least three dominant propagating modes in the CBCPW portion of Fig. 1, namely, the CPW mode, the *c-mode-like* mode, and the π*-mode-like* mode. The latter two correspond to the MSL (microstrip-like) mode and the CSL (coupled slotline) mode when the two side planes are of equal width. Besides, the microstrip mode can propagate beyond the open-end. The interaction of these scattered propagating modes caused by the open-end and the shorted side planes can be complex enough that certain anomalous results obtained by measurement may disagree with theoretical computations based on either simplified analysis using the quasi-TEM approach or simplified model assuming infinitely extended side planes of the CPW.

This letter will report the scattered waves invisible to the previously published works that used the simplified model or analysis method. The theoretical results are obtained by a space-domain integral equation technique capable of near-discontinuity de-embedding using the generalized scattering matrix (GSM) description, without needing the knowledge, and thus avoiding the confusion over the definition, of the characteristic impedance of the guided-wave structure [10]. First, an experimental verification of a discontinuity problem with microstrip-CPW-open-end configuration is conducted, confirming the use of the rigorous integral equation method and indicating that the above-mentioned dominant modes are sufficient to describe the discontinuity problem of Fig. 1. Next, the comprehensive scattering analyses of Fig. 1 show that there is a noticeable amount of mode conversion in both reflected and transmitted modes under a variety of test conditions. Throughout this letter, we use the GSM notation $S_{ij}(m,n)$, which represents the scattering parameter of the mth mode scattered at physical port i for the nth mode incident on physical port j.

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The authors are with the Institute of Electrical Communication Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan.

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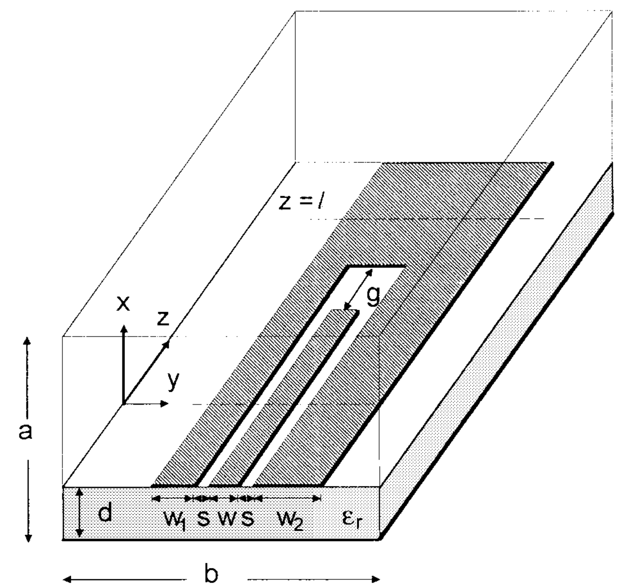

Fig. 1. Conductor-backed CPW open-end discontinuity with unequal side-plane widths.

II. Experimental Validity Check

The inset of Fig. 2 shows the experimental circuit layout to verify the theoretical approach employed in this work. The prototype consists of a 50-Ω microstrip connected to the CPW open-end circuit. The theoretical evaluation of $S_{11}(1,1)$ at port 1 $(z=-l_1)$ is intentionally divided into two steps. First, we arbitrarily segment the prototype at $z = lx(0<lx<l)$ and analyze segments A and B separately. The two GSM solutions are then combined to obtain $S_{11}(1,1)$ [10]. During the computation of GSM's, the three dominant modes mentioned above are included, although we may consider

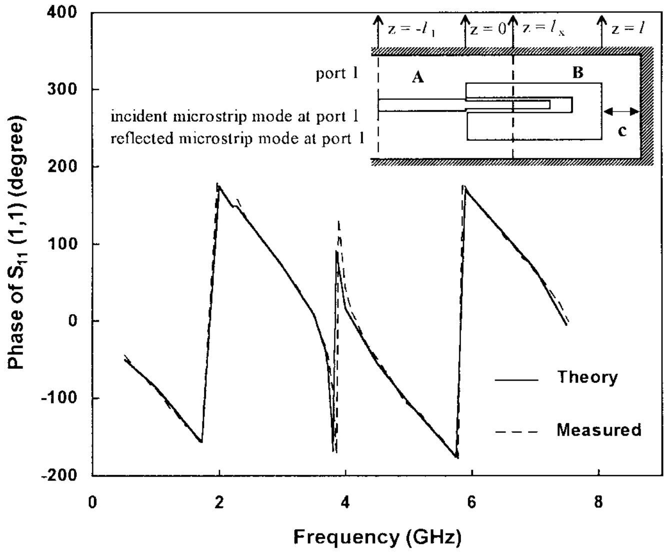

Fig. 2. Calculated and measured results of the one-port circuit in the inset of the figure. $\varepsilon_r = 10.2, d = 0.635$ mm, $w = s = 0.8$ d, $w_1 = 1.216$ mm, $w_2 = 2w_1, g = 1.6$ d, $l = 13.048$ mm, $l_1 = 5$ mm, and $c = 1.952$ mm.

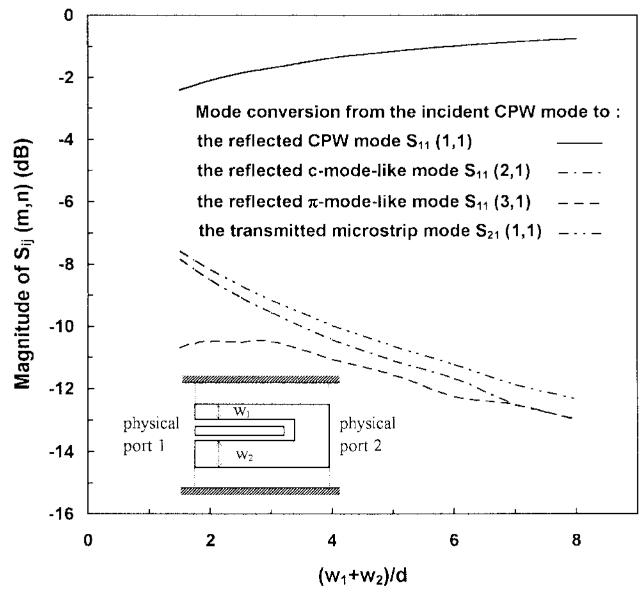

Fig. 3. Mode conversion of an incident CPW mode against side-plane width for $w_2/w_1 = 2$ and $f = 5$ GHz. $\varepsilon = 10.2, d = 0.635$ mm, $a = 11$ d, $b = 10$ mm, $w = 0.7$ d, $s = 0.35$ d, and $g = 0.8$ d.

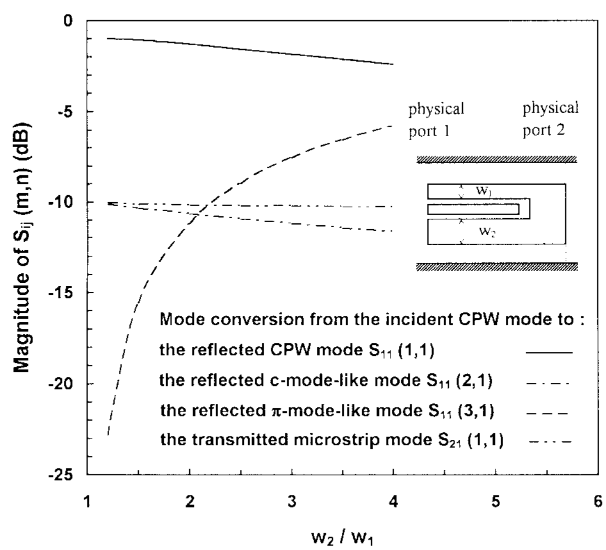

Fig. 4. Mode conversion of an incident CPW mode against asymmetry ratio of side-plane widths for $w_1 + w_2 = 2.667$ mm and $f = 5$ GHz. Other circuit dimensions are the same as those in Fig. 3.

as many higher order modes as we wish in the present approach [10]. The magnitude of the theoretical $S_{11}(1,1)$ for this one-port circuit is a constant of one (satisfied within 0.001%) because of the metal enclosure. Therefore, Fig. 2 shows only the phase comparison for clarity. As in Fig. 2, the excellent agreement between measured and theoretical data has two-fold significance. First, our rigorous full-wave field-theoretical approach is accurate. Furthermore, the segmented scattering analyses of the particular case indicate that the three propagating modes mentioned above can approximate the discontinuity problem very well. Notice that the two resonant locations at around 2.2 and 3.8 GHz can be related to the result of exciting the π-mode-like mode and c-mode-like mode, respectively.

III. Numerical Results and Discussions

The studies on the asymmetric CBCPW open-end circuit of Fig. 1 focus on the effects of side plane width (Fig. 3), degree of asymmetry (Fig. 4), and frequency dependence (Fig. 5). First, we change the total side-plane width (w_1+w_2) at 5 GHz while keeping the same w_2/w_1 ratio. The theoretical results are plotted in Fig. 3. Like the symmetric case [2], increasing the total side-plane width $(w_1 + w_2)$ also reduces the amount of mode conversion associated with the reflected c-mode-like mode $(S_{11}(2,1))$, the reflected π-mode-like mode $(S_{11}(3,1))$, and the transmitted microstrip mode $(S_{21}(1,1))$. These extra dominant modes besides the CPW mode have more of their electromagnetic fields concentrating underneath the wider side planes, thus reducing the amount of CPW mode conversion. In this particular case, the total power converted from the incident CPW mode into the other modes reduces from 43% to 16% as the total side-plane width increases from 1.5 d to 8 d. Nevertheless, for wider side planes, care must be exercised to avoid the emerging higher order MSL modes, which can cause unwanted effects such as resonance and power leakage [11].

In contrast to Fig. 3, Fig. 4 shows the effect of w_2/w_1 ratio while maintaining a constant side plane width, $w_1 + w_2 = 2.667$ mm. As the ratio increases, the power converted to the π-mode-like mode increases considerably and the power converted to the c-mode-like and microstrip modes decreases slightly. The magnitude of the reflected π-mode-like mode $(|S_{11}(3,1)|)$ becomes negligible as w_2/w_1 ratio approaches unity. This is in accordance with the fact that a symmetric guided-wave structure cannot generate an odd mode by an even mode input excitation. This π-mode-like mode may cause problems since equivalently 26% of the incident CPW power is reflected back to the input when w_2/w_1 is 4 while the CPW still maintains equal slot width. On the other hand, the reflected c-mode-like mode and the transmitted microstrip mode carry away approximately 8% and 10% of the incident energy,

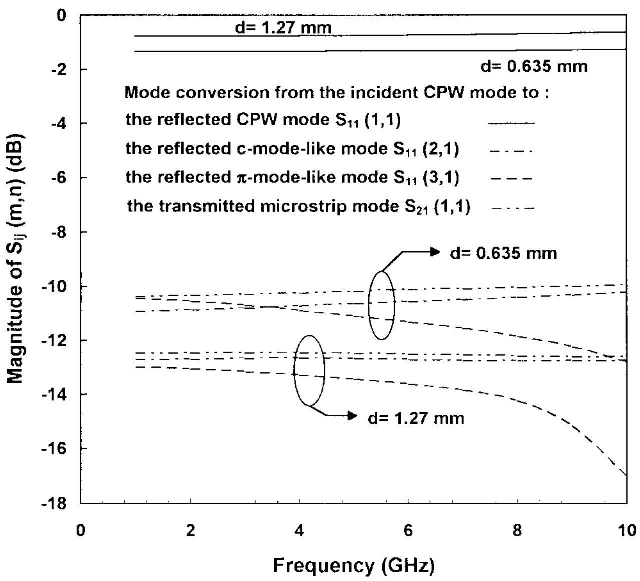

Fig. 5. Frequency characteristics of the mode conversion. The circuit dimensions are the same as those in Fig. 3 while $w_2/w_1 = 2$ and $w_1 + w_2 = 2.667$ mm. The CPW open-end circuit maintains its dimensions for $d = 1.27$ mm.

respectively, regardless of the change of the asymmetry ratio w_2/w_1.

Finally, Fig. 5 shows the dispersion characteristics of the mode conversion for two different substrate thicknesses. As shown in Fig. 5, the amount of the conversion is significant at low frequencies and is reduced for the thicker substrate. Alternatively, one may expect that the amount of mode conversions depicted in Fig. 5 can be reduced by keeping the ratio of $w+2s$ to d small. The same phenomena had been observed in many symmetric cases [2], [6]. Besides, the π-mode-like mode is less likely to be excited as frequency increases. At the higher frequencies, however, other higher order modes may propagate and they should be incorporated into the computation.

Notice that all the case studies presented so far indicate that the power converted to the c-mode-like mode approximates the microstrip mode, since both modes have similar field distributions and propagation constants. The above discussions imply that the π-mode-like mode could be easily excited at a discontinuity when the side plane asymmetry is high, regardless of what kinds of air-bridge techniques are used [1].

IV. Conclusion

A novel approach making detailed scattering analyses of a CPW open-end discontinuity problem reveals the tangled mode conversion processes in the simple case study. The modeling technique will allow uniplanar IC designers better physical insight looking into anomalous circuit behaviors caused by coupling and resonance.

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