A Versatile Moment Method Solution of the Conventional and Modified Coplanar Waveguide T-Junctions

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***Abstract*—The conventional and modified coplanar waveguide (CPW) T-junctions, both symmetric and nonsymmetric, are investigated using the full wave moment method with duality for the electric and magnetic currents. The method is shown to be accurate and computationally more efficient than the FDTD method previously used to solve these T-junctions. Our results show that the dispersion in the S -parameters of the different types of CPW T-junctions investigated can be minimized by a proper choice of the dimensions and locations of the air-bridges. The versatility of the method is demonstrated by its ability to solve complicated CPW structures with different types of air-bridges such as the modified CPW T-junction.**

I. Introduction

RECENTLY, coplanar waveguides (CPW) have attracted much attention due to their advantages, such as the ease of shunt and series connections, the low radiation [1], the low dispersion and thus avoiding the use of thin fragile substrates [2].

For CPW an air-bridge is considered a fundamental component needed to suppress the parasitic coupled (odd) slot-line mode which causes the CPW to radiate excessively [3]. This mode has opposite potentials on the two ground planes with zero potential at the center strip. It is generated in CPW nonsymmetric circuits, like T-junctions, due to the different path lengths propagated by the potential (magnetic current) wave in each slot. The air-bridge, however, equates the potentials of the two ground planes and therefore equates the voltage drop across each slot at the air-bridge location. This causes the magnetic current flowing in the adjacent slots to be equal and opposite and thus eliminates the coupled (odd) slot-line mode.

To include the air-bridges when solving the CPW nonsymmetric circuits, different techniques were used. Dib *et al.* [4] and Bromme *et al.* [5] used quasi-static models for the air-bridges. This technique is, however, potentially inaccurate at high frequencies.

Manuscript received April 13, 1992; revised August 3, 1992. This work was supported by the NSERC (National Science and Engineering Research Council) ITRC (Information Technology Research Center) and the University of Waterloo.

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IEEE Log Number 9206299.

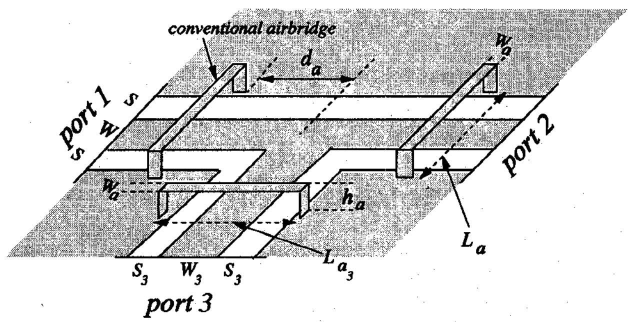

Fig. 1. The conventional CPW T-junction.

For accuracy even at high frequencies, other researchers used the full wave FDTD method [6]–[7] and the finite difference method in the frequency domain [8].

In a previous paper [9], we presented an accurate and computationally efficient moment method with duality, which can solve general CPW circuits with and without air-bridges. This method uses the integral equation technique [10] combined with the moment method [11] to solve these CPW structures. However, we only applied this method to solve the CPW with the conventional air-bridge shown in Fig. 1 [9]. In the present paper, we demonstrate the versatility of our method by applying it to different CPW structures with different types of air-bridges. The chosen structures to be analyzed are: 1) The conventional CPW T-junction which uses the conventional air-bridge, as shown in Fig. 1. 2) The modified CPW T-junction which uses the modified air-bridge, as shown in Fig. 2. This modified T-junction was originally proposed by Koster [12].

Both the conventional and modified CPW T-junctions were previously analyzed by Rittweger *et al.* [7] using the FDTD method. This method is time consuming because it requires the discretization of the whole volume occupied by the T-junctions. On the other hand, our application of the moment method requires only the discretization of the slots and the air-bridges. This limited discretization, combined with the efficient calculation of the Green's functions for CPW using the complex image technique [13], makes our method computationally more efficient.

This paper is organized as follows: In Section II we only briefly explain the theoretical formulation of the CPW with the modified air-bridge; the formulation for the CPW with

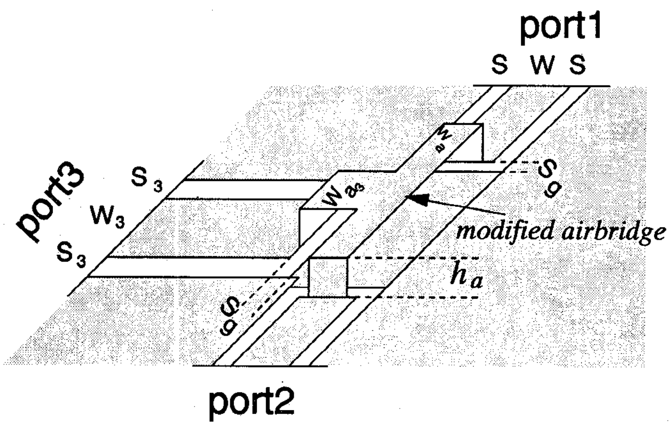

Fig. 2. The modified CPW T-junction.

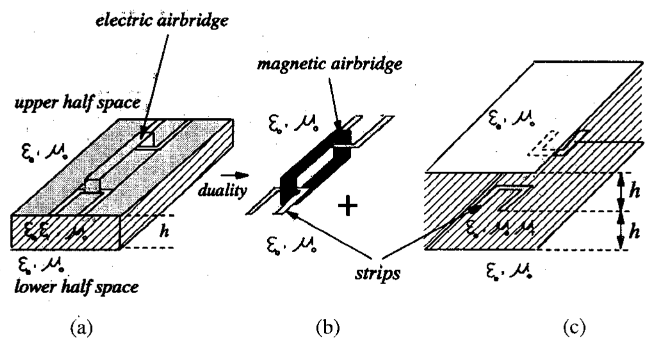

Fig. 3. Splitting a CPW problem with the modified air-bridge into two parallel strips subproblems through duality: (a) The original CPW problem with the modified air-bridge. (b) The upper subproblem. (c) The lower subproblem.

the conventional air-bridge was explained in [9]. In Section III we present numerical results for the S-parameters of the conventional and modified CPW T-junctions, both symmetric and nonsymmetric, as compared to previously published experimental and theoretical results with an investigation of the behavior of these T-junctions.

II. Theoretical Formulation

1. The Duality Formulation for the CPW with the Modified Air-Bridge

The main assumptions in formulating the integral equations for the CPW with air-bridge are that the CPW is nonshielded and that the center strip, the ground planes and the air-bridges are infinitely thin perfect conductors and that the dielectric is lossless. The duality formulation for the CPW with the conventional air-bridge, shown in Fig. 1, was explained in [9]. Therefore, in this paper we only explain the duality formulation for the CPW with the modified air-bridge shown in Fig. 3(a). This modified air-bridge can be considered as the main building block of the modified T-junction shown in Fig. 2.

The CPW has two slots. Therefore, similar to a slot antenna, the two slots and the ground plane can be transformed into two equivalent strips without ground plane through the duality principle of electric and magnetic currents [14]. Similarly, the electric conductor air-bridge can be transformed into its dual, a magnetic conductor air-bridge. However, because of the dielectric substrate, the duality principle has to be applied separately for the upper and lower half spaces of the CPW with the modified air-bridge, as shown in Fig. 3(a)–(c).

For the upper half space with no dielectric slab, the transformation by duality results in an equivalent full space problem of two short ended parallel strips in free space joined by a magnetic air-bridge loop as shown in Fig. 3(b). This magnetic air-bridge loop results from the dual air-bridge and its image with respect to the plane of the strips. For the lower half space with a dielectric slab, the transformation results in the full space problem of two short ended parallel strips embedded inside a magnetic slab (characterized by ϵ_o, μ_r, μ_o with $\mu_r = \epsilon_r$) of Fig. 3(c).

From this point forward, the formulation for the CPW with either type of air-bridge is identical. This formulation was explained in [9]. Briefly, the next step will be to satisfy the boundary conditions on the strips and the magnetic air-bridges of the dual problem. This leads to a pair of coupled mixed potential integral equations whose unknowns are the electric current on the strips and the magnetic current on the air-bridges. These coupled equations are then solved using the Galerkin moment method. In addition, the Green's functions for the upper subproblem of Fig. 3(b) are simply the free space Green's functions, while those for the lower subproblem of Fig. 3(c) are obtained using the complex image technique [13]. This is explained in detail in [9].

III. Numerical Results and Discussions

In this section, we investigate the behavior of two different types of CPW T-junctions: The conventional T-junction shown in Fig. 1, and the modified T-junction shown in Fig. 2. This investigation includes both symmetric T-junctions whose three arms have the same characteristic impedance (Z_o), and nonsymmetric T-junctions with the arm connected to port 3 having a characteristic impedance (Z_{0_3}) while the other two arms have a characteristic impedance (Z_0).

Our investigation finds the designs for reducing the frequency dispersion in the S-parameters of the different types of T-junctions so that these parameters may approach the ideal (dispersionless) behavior. This is important because these T-junctions occur very frequently in large CPW circuits, and their dispersion is therefore very significant especially in the millimeter frequency range.

The ideal (dispersionless) S-parameters, which ignore the different parasitic effects of the T-junctions, can be obtained using transmission line theory. These ideal parameters are found to be: $|S_{11}| = |S_{33}| = 1/3, |S_{21}| = |S_{31}| = 2/3$ for the symmetric CPW T-junctions, and $|S_{11}| = 1/\{1 + 2Z_{o_3}/Z_o\}, |S_{21}| = 1/\{1 + Z_o/(2Z_{o_3})\}, |S_{31}| = |S_{21}|\sqrt{Z_o/Z_{o_3}}, |S_{33}| = |\{Z_o - 2Z_{o_3}\}/\{Z_o + 2Z_{o_3}\}|$ for the nonsymmetric CPW T-junctions.

1. The Conventional T-Junction shown in Fig. 1

This subsection discusses only the symmetric conventional T-junctions which have identical arms and identical air-bridges

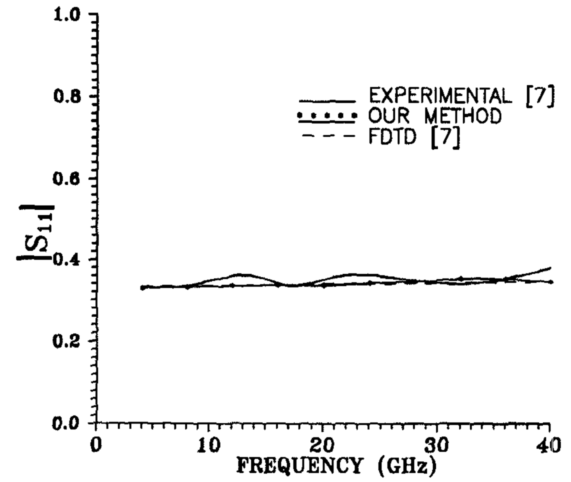

Fig. 4. $|S_{11}|$ versus frequency for the symmetric conventional CPW T-junction. ($W = 75\,\mu\text{m}, S = 50\,\mu\text{m}, h = 300\,\mu\text{m}, \epsilon_r = 12.9, h_a = 3.125\,\mu\text{m}, W_a = 75\,\mu\text{m}, L_a = 185\,\mu\text{m}, d_a = 174.5\,\mu\text{m}$).

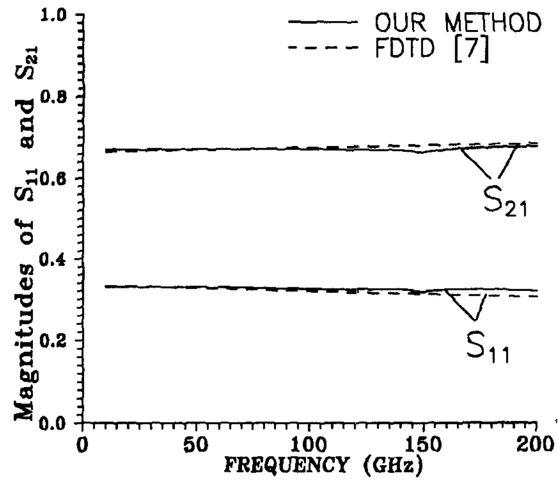

Fig. 5. The S-parameters of the symmetric conventional CPW T-junction versus frequency. ($W = 15\,\mu\text{m}, S = 10\,\mu\text{m}, h = 60\,\mu\text{m}, \epsilon_r = 12.9, h_a = 3.125\,\mu\text{m}, W_a = 15\,\mu\text{m}, L_a = 37\,\mu\text{m}, d_a = 34.9\,\mu\text{m}$).

(i.e. center conductor widths: $W_3 = W$, slot gaps: $S_3 = S$ and air-bridge lengths: $L_{a_3} = L_a$ in Fig. 1).

a) Comparison with published results: To check the accuracy of our results for the S-parameters of the symmetric conventional T-junction, they are compared with similar experimental and theoretical results obtained by Rittweger *et al.* [7] using the FDTD method. This comparison is carried out for the two sets of dimensions used in Figs. 3 and 6 of [7]. In both his figures, Rittweger failed to mention the values of ϵ_r and h. We therefore chose these values such that the characteristic impedance of each arm is 50 Ω which is the practical choice for measurements. This corresponds to choosing $\epsilon_r = 12.9$ and $h = 300\,\mu\text{m}$. However, the particular choice of h, as long as it is larger than $W + 2S$, is found to have negligible effect on the S-parameters of this T-junction. Rittweger also failed to mention the length of each air-bridge (L_a). This length is found to be insignificant to the resultant S-parameters.

The results of the comparisons are shown in Figs. 4 and 5. These two figures show very good agreement with the experimental and the FDTD-theoretical results of [7] over the whole frequency ranges investigated. This demonstrates the accuracy of our method as applied to these T-junctions.

From the results of Fig. 5, we noticed that $|S_{11}|$ decreases with increasing frequency by about 5% over the frequency range investigated. This behavior was also observed by [7] as shown in Fig. 5. This behavior cannot be attributed to the dispersion caused by the air-bridges capacitances which tend to increase $|S_{11}|$ with increasing frequency. We believe that this behavior can only be caused by the dispersion due to the coupled slot-line mode. This mode is reduced by the air-bridges but not completely eliminated. Therefore, to approach the ideal dispersionless behavior of this T-junction, we may minimize the parasitic mode or counterbalance the decrease of $|S_{11}|$ with frequency by increasing the air-bridges capacitances which cause the opposite trend. The detail is explained below.

b) The effect of the air-bridge width (W_a): We found numerically that, by increasing W_a, the capacitance of each air-bridge increases. This tends to increase $|S_{11}|$ slightly with increasing frequency which will compensate for the small dispersion due to the parasitic mode. Therefore, the resultant dispersion is reduced as W_a is increased as shown in Fig. 6. Finally, a value of W_a is reached after which no further improvement can be gained by increasing W_a. On the contrary, the dispersive effects due to the air-bridge capacitances will then dominate and $|S_{11}|$ will tend to increase with frequency.

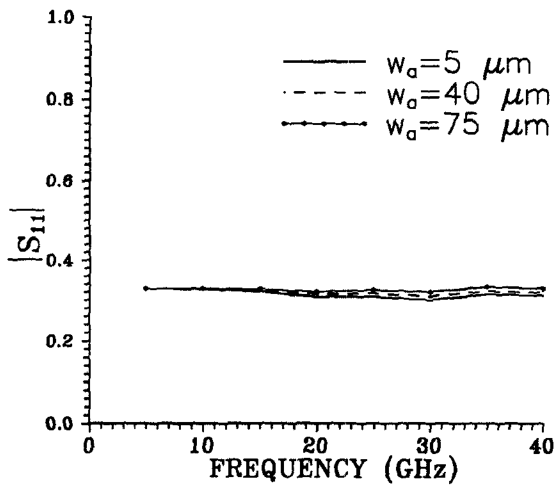

Fig. 6. The effect of the width of the air-bridge (W_a) on $|S_{11}|$ for the symmetric conventional CPW T-junction. ($W = 75\,\mu\text{m}, S = 50\,\mu\text{m}, h = 300\,\mu\text{m}, \epsilon_r = 12.9, h_a = 3.125\,\mu\text{m}, L_a = 185\,\mu\text{m}, d_a = 174.5\,\mu\text{m}$).

c) The effect of the air-bridge height (h_a): We found that h_a has a negligible effect on the S -parameters of the conventional T-junction. For h_a to have an effect, it must be less than 1 μm, which is impractical.

d) The effect of the air-bridge location (d_a): It is found numerically that by moving the air-bridges farther away from the center of the T-junction (i.e. increasing d_a shown in Fig. 1), less coupled slot-line mode can be eliminated by these air-bridges. This causes the T-junctions to radiate more as d_a is increased. Fig. 7 shows the percentage power loss versus air-bridge location (d_a) at different frequencies. This percentage power loss can be obtained from the S-parameters of the

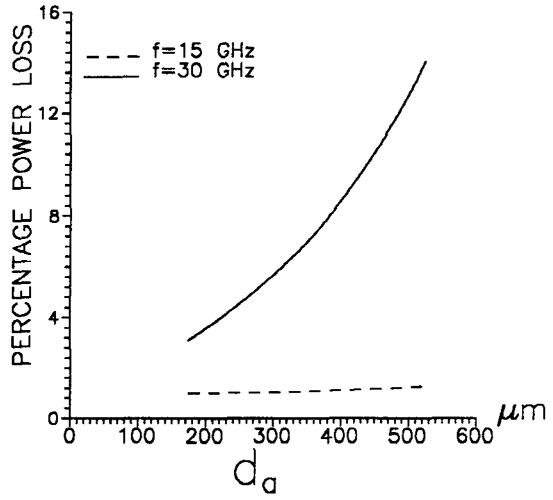

Fig. 7. The percentage power loss versus the location of each air-bridge (d_a) for the symmetric conventional CPW T-junction. ($W = 75\,\mu$m. $S = 50\,\mu$m. $h = 300\,\mu$m, $\epsilon_r = 12.9, h_a = 3.125\,\mu$m, $W_a = 40\,\mu$m. $L_a = 185\,\mu$m)

T-junction as:

$$(1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2)100\%$$

This power loss consists of two parts: the radiation loss mainly resulting from the parasitic coupled slot-line mode, and the surface wave loss. For this paper the two parts are lumped together. Fig. 7 shows an almost exponential increase of the power loss with increasing d_a. Therefore we conclude that the air-bridges should be as close as possible to the center of the conventional T-junction to minimize the slot-line mode and hence minimize the radiation loss and the dispersion.

2. The Modified T-Junction Shown in Fig. 2:

This subsection discusses the symmetric modified T-junctions which have identical arms and a symmetric air-bridge (i.e. center conductor widths: $W_3 = W$. slot gaps $S_3 = S$ and air-bridge widths: $W_{a_3} = W_a$ in Fig. 2).

a) Comparison with published results: For the same two sets of dimensions used in Figs. 4 and 5, very good agreement is obtained between our results for the S-parameters of the symmetric modified T-junction and similar experimental and FDTD-theoretical results from [7]. This is shown in Figs. 8 and 9. It is important to mention that the gap width under the air-bridge (S_g) shown in Fig. 2 has some effect on the S-parameters. This effect will be explained in part (d) of this subsection.

The results of Fig. 8 show an increase in $|S_{11}|$ with increasing frequency. This is due to the parasitic capacitance of the air-bridge which has larger dimensions as compared with the air-bridges used for the conventional T-junction. Therefore, for the modified T-junction, the dispersive effects of the air-bridge's capacitance dominate over the dispersive effects due to the coupled slot-line mode. The effect of the air-bridge's dimensions on the behavior of the S-parameters for the symmetric modified T-junction are explained below.

b) The effect of the air-bridge width (W_a)*:* We found that by decreasing W_a, the dispersion in the S-parameters decreases and their behavior approaches the ideal behavior as

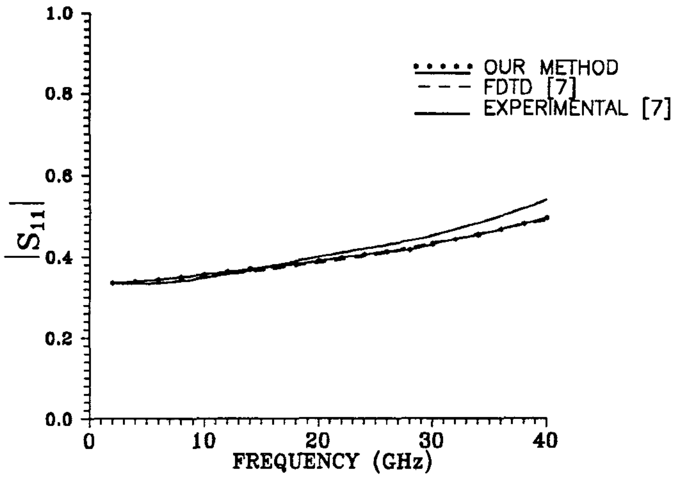

Fig. 8. $|S_{11}|$ versus frequency for the symmetric modified CPW T-junction. ($W = 75\,\mu$m. $S = 50\,\mu$m. $h = 300\,\mu$m, $\epsilon_r = 12.9, h_a = 3.125\,\mu$m, $W_a = 75\,\mu$m. $S_g = 0.2S$).

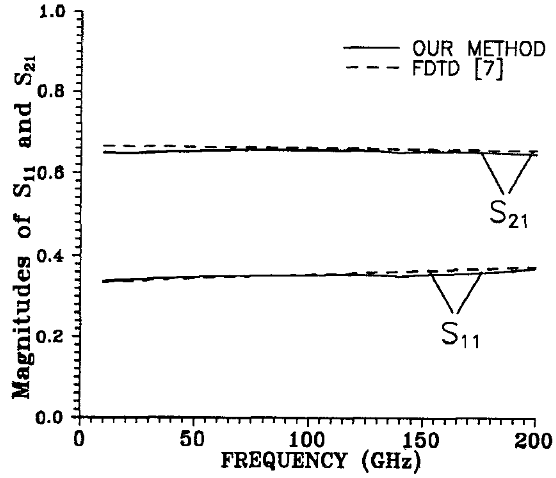

Fig. 9. The S-parameters of the symmetric modified CPW T-junction versus frequency. ($W = 15\,\mu$m. $S = 10\,\mu$m, $h = 60\,\mu$m, $\epsilon_r = 12.9, h_a = 3.125\,\mu$m. $W_a = 15\,\mu$m. $S_g = S$).

shown in Fig. 10. However, W_a cannot be made very small in practice because as W_a is decreased the conductor loss due to the air-bridge, which carries all the strip current, increases. Therefore, a compromise has to be made in this case between reducing the dispersion and increasing the conductor loss.

c) The effect of the air-bridge height (h_a)*:* We found that by increasing h_a, the S-parameters approach the ideal dispersionless behavior due to the decrease in the air-bridge capacitance. This effect can be inferred from Figs. 8 and 9. By simply scaling up the dimensions of Fig. 9 by a factor of 5 while scaling down the frequency by the same factor, the S-parameters of Fig. 9 should remain unchanged. After this scaling, Figs. 8 and 9 will correspond to the same dimensions except that Fig. 9 has a 5 times higher air-bridge. This clearly shows that the S-parameters of the modified T-junction have less dispersion as h_a is increased.

d) The effect of the width of the gap under the air-bridge (S_g)*:* We found that by increasing S_g, the dispersion in $|S_{11}|$ decreases and the S-parameters approach the ideal behavior

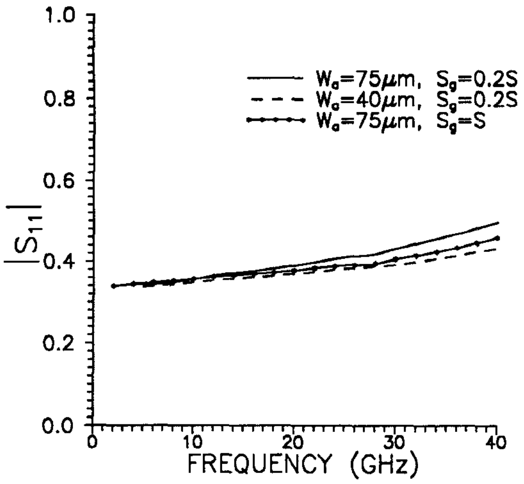

Fig. 10. The effects of W_a and S_g on $|S_{11}|$ for the symmetric modified CPW T-junction. ($W = 75\,\mu\text{m}, S = 50\,\mu\text{m}, h = 300\,\mu\text{m}, \epsilon_r = 12.9, h_a = 3.125\,\mu\text{m}$).

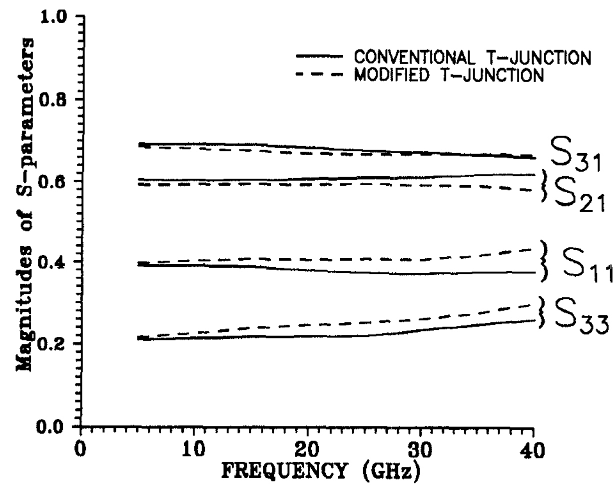

Fig. 11. The S-parameters of the nonsymmetric conventional and modified CPW T-junctions versus frequency. ($W = W_3 = 75\,\mu\text{m}, S = 50\,\mu\text{m}, S_3 = 20\,\mu\text{m}, h = 300\,\mu\text{m}, \epsilon_r = 12.9, h_a = 3.125\,\mu\text{m}, W_a = W_{a_3} = 40\,\mu\text{m}, S_g = 0.2S, L_a = 185\,\mu\text{m}, d_a = 174.5\,\mu\text{m}$).

as shown in Fig. 10. This trend can be attributed to the end capacitance generated by the gap under the air-bridge. This end capacitance decreases with increasing S_g thereby decreasing the net capacitance to ground at the air-bridge location. This causes $|S_{11}|$ to decrease with increasing S_g until a value of S_g is reached after which the capacitance and hence the S-parameters remain virtually unchanged. The behavior of the open end capacitance in CPW was discussed in [15].

3. The Power Loss for the Conventional and Modified T-Junctions:

Fig. 7 shows the power loss (due to the radiation and the surface waves) of the conventional T-junction versus the location of each of its air-bridges (d_a). This figure was explained in part (d) of section (III-1). However, in Fig. 7 we could not also plot the power loss of the modified T-junction versus the air-bridge location (d_a) because this T-junction has a fixed air-bridge location (at the center of the junction). However, at both frequencies given in Fig. 7, we found that the power loss of the modified T-junction is comparable with that of the conventional T-junction if the latter T-junction has its air-bridges located at $d_a = 200\,\mu\text{m}$. The power loss for the conventional T-junction increases with increasing frequency as shown in Fig. 7, and a similar frequency behavior is observed for the modified T-junction.

4. The Nonsymmetric Conventional and Modified T-Junctions:

In these T-junctions, the arm connected to port 3 has a characteristic impedance Z_{o_3}, while the other two arms have a characteristic impedance Z_o. The general expressions for the ideal S-parameters of both types of T-junctions are given at the start of Section II. For a T-junction with $Z_o = 50\,\Omega$ and $Z_{o_3} = 38.44\,\Omega$, these ideal S-parameters are $|S_{11}| = 0.394, |S_{21}| = 0.606, |S_{31}| = 0.691$ and $|S_{33}| = 0.212$. The actual S-parameters for both types of T-junctions are shown in Fig. 11. This figure shows that the nonsymmetric T-junctions of both types behave in the same way as the symmetric ones and therefore the previous ways of minimizing the dispersion can still be applied.

IV. Conclusions

In this paper, we applied a full wave method to solve two distinct types of T-junctions, the conventional T-junction and the modified T-junction. These T-junctions can be either symmetric or nonsymmetric. The method used is the mixed potential integral equation technique combined with the moment method. The Green's functions for the open CPW are obtained using the accurate and very efficient complex image technique.

This method was applied once before for CPW to solve a 2-port CPW filter [9] which only uses the conventional type of air-bridge shown in Fig. 1. In this paper, our method is applied to the solution of 3-port CPW circuits, namely the conventional and modified CPW T-junctions, which use the two types of air-bridges shown in Figs. 1 and 2, respectively. This application, therefore, shows the versatility of the method.

Our results for the S-parameters of both types of T-junctions are compared with previously published experimental and theoretical results obtained using the FDTD method [7]. Very good agreement is obtained using only 93 matching points on the strips and 15 matching points on the air-bridges for either type of T-junction. This results in 5 minutes for each frequency on a 33 MHZ 80386 PC. This clearly shows the computational efficiency of our solution of these T-junctions as compared to the FDTD-method which is time consuming and requires a large computer memory.

For both the conventional and modified T-junctions, our results show that the S-parameters are generally close to the ideal S-parameters with some dispersion resulting mainly from the effect of the parasitic capacitances of the air-bridges and the effect of the parasitic coupled slot-line mode. The first effect tends to increase $|S_{11}|$ with increasing frequency, while the second effect tends to decrease $|S_{11}|$ slightly with increasing frequency. The small dispersion in the S-parameters for both types of T-junctions can be further reduced by properly choosing the dimensions and locations of the air-bridges as explained in Sections III-1 and III-2.

In addition, a comparison is carried out between the power loss, due to radiation and surface waves, of the conventional and modified CPW T-junctions. This comparison showed that both types of T-junction have a comparable power loss if they have similar dimensions and if the air-bridges of the conventional T-junction are located very close to the center of this T-junction.

Finally, we have demonstrated in this paper that the moment method, combined with the duality principle, is versatile in the sense that it can be applied to complicated CPW circuits, such as the modified T-junction, with ease and with a substantial economy in computation.

Acknowledgment

The authors would like to thank Dr. J. J. Yang for his helpful suggestions and valuable comments.

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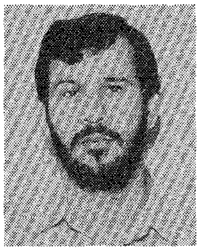

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