N94-20500

A COMPREHENSIVE THEORETICAL AND EXPERIMENTAL STUDY OF COPLANAR WAVEGUIDE SHUNT STUBS

Nihad I. Dib[†], George E. Ponchak[*] and Linda P. B. Katehi[†]

[†] *Radiation Lab., University of Michigan, 3228 EECS Building, Ann Arbor, MI 48109-2122*
[*] *NASA, Lewis Research Center, 21000 Brookpark Rd, MS 54-5, Cleveland, OH 44135*

ABSTRACT

A comprehensive theoretical and experimental study of straight and bent CPW shunt stubs is presented. In the theoretical analysis, the CPW is assumed to be inside a cavity, while, the experiments are performed on open structures. A hybrid technique has been developed to analyze the CPW discontinuities which has been proven to be accurate since the theoretical and experimental results agree very well. Throughout this study, the effect of the cavity resonances on the behavior of the stubs with and without air-bridges is investigated. In addition, the encountered radiation loss due to the discontinuities is evaluated experimentally.

INTRODUCTION

Recently, with the push to high frequencies and monolithic technology, coplanar waveguides (CPWs) have experienced a growing interest due to their appealing properties. While there is no need for via holes in CPW circuits, air-bridges are fundamental components required to connect the ground planes for suppression of the coupled slotline mode. In the past few years, there has been several attempts to characterize, theoretically and/or experimentally, CPW discontinuities with air-bridges or bond wires [1-5]. The Finite Difference Frequency Domain method was used in [6] to treat two common types of CPW air-bridges where it was found that the reflection coefficient (or S_{11}) varies linearly with frequency. This fact suggests that a typical air-bridge can be modeled as a frequency dependent lumped element [1, 2]. With this fact in mind, a hybrid technique has been developed by the authors [2] to analyze CPW discontinuities with air-bridges. In this technique, at first, the frequency dependent equivalent circuit of the discontinuity, with the air-bridges removed, is derived using a full wave analysis which is based on the Space Domain Integral Equation (SDIE) method [7]. Then, this equivalent circuit is modified by incorporating the air-bridge parasitic inductance and capacitance which are evaluated using a quasi-static model.

In this paper, the above mentioned hybrid technique is used to study a variety CPW shunt stub geometries (Fig.2) and the validity of the model is verified by performing extensive measurements. The scattering parameters of the stubs with and without air-bridges are presented and a very good agreement is found between theoretical and experimental data. In addition, the effect of cavity resonances (since a shielded structure is assumed in the theory) on the behavior of these stubs is shown. Moreover, the encountered radiation loss due to the discontinuities is investigated experimentally.

THEORY

In the theoretical analysis, the CPW under consideration (Fig.1) is assumed to be inside a rectangular cavity of perfectly conducting walls. As pointed out in the introduction, the hybrid technique developed in [2] is used to analyze the shunt CPW stubs shown in Fig.2. First, the frequency dependent equivalent circuit of the discontinuity, with the air-bridges removed, is derived using the Space Domain Integral Equation (SDIE) method [7]. Then, this equivalent circuit is modified by incorporating the parasitic reactances introduced by the air-bridges. These reactances, a series inductance and a shunt capacitance, are evaluated by modeling the air-bridges as sections of an air filled microstrip line or parallel plate waveguide. The SDIE method will not be discussed here since it has been presented in detail in [7]. However, a slight modification on the equivalent circuit presented in [2] is needed as discussed below.

After applying the method of moments, the electric field in the slot apertures, which forms standing waves of the fundamental coplanar waveguide mode away from the discontinuity, is obtained. Notice that the slotline mode will not be excited in the CPW feed lines since the discontinuities considered here (Fig.2) are symmetric with respect to the center axis of the feeding lines. Consequently, an ideal transmission line method can be used to determine the scattering parameters and evaluate the elements of the equivalent circuit shown in Fig.3a. It should be noticed that in the case of straight stubs, the two reactances X_1 and X_2 are equal due to the symmetry of the circuit. Fig.3b shows the new equivalent circuit after taking the air-bridges into consideration. The air-bridges can be modeled as sections of an air-filled microstrip line [1], and simple design formulas can be used to evaluate the parasitic capacitance C_a and inductance L_a. Alternatively, a parallel plate waveguide model can be employed to evaluate the same parasitic effects. It is found that the difference in the values of the parasitic reactances as predicted by the two models has a negligible effect on the preformance of the circuit. Finally, new scattering parameters are evaluated from the modified equivalent circuit.

RESULTS AND DISCUSSION

In the numerical results shown here, the considered CPW discontinuities are suspended inside a rectangular cavity , as shown in Fig.1, with $h = 400\mu m$, $\epsilon_{r1} = 13$, $\epsilon_{r2} = 1$, $S = 75\,\mu m$, $W = 50\,\mu m$, and $h_1 = h_2 = 1.2\,mm$. On the other hand, the slots and center conductor of the CPW stubs have equal widths of $25\,\mu m$. In addition, in the case of the open-end stubs, the width of the open-end is $25\,\mu m$. In all examples presented here, the stubs are placed symmetrically at the center of the cavity.

The experiments were performed in an open environment with the CPW circuits fabricated on $400\,\mu m$ thick GaAs using lift-off processing. The CPW center strip and ground planes consist of $200A$ of Cr and $1.5\,\mu m$ of Au. The air-bridges have $10\,\mu m$ square posts and are $14\,\mu m$ wide. The air-bridge thickness and height are $1.0\,\mu m$ and $3.0\,\mu m$ respectively. The GaAs circuit was placed on a piece of $3.175\,mm$ 5880 RT/duroid which has a dielectric constant of 2.2.

The circuits were tested with HP 8510 network analyzer and a Cascade probe station. The calibration standards for a TRL calibration were fabricated on the wafer to allow calibration to the reference planes of the CPW stubs. To cover the 5-40 GHz bandwidth, three delay lines were used. The probe positioning on the wafer was determined to be repeatable to within $3\,\mu m$ which creates a maximum error in the phase of S_{21} of 0.76° at 40 GHz.

Fig.4 shows the S-parameters of the straight open-end stub (Fig.2a) of length $L = 1100\,\mu m$ and with the air-bridges removed as a function of frequency. It is noticed that the theoretical and experimental results agree very well up to the first resonance, after which, discrepancy in noticeable. This is attributed to the radiation loss encountered in the measurements which is mainly due to the excitation of the slotline mode in the CPW stubs in the absence of the air-bridges. It is found that the anomalous behavior seen between 41 and 45 GHz is due to a cavity resonance at 43 GHz which corresponds to the LSM_{121} mode excited in the partially filled lower cavity (the cavity width was chosen to be $3.425\,mm$). It is interesting to note that the LSM_{111} and LSM_{131} modes which have resonant frequencies of 38 and 48 GHz, respectively, do not show any effect on the stub. This may be attributed to the fact that the longitudinal electric field component of the LSM_{111} and LSM_{131} is an odd function with respect to a symmetry plane placed at the center of the cavity, as opposed to the LSM_{121} mode whose longitudinal component is an even function around the same plane. Thus, cavity modes, which have an even variation with respect to this plane, interact with the slotline mode in the stubs, which in turn affects the value of the series reactance in the equivalent circuit. It is expected that if the CPW structure is placed asymmetrically inside the cavity, other cavity resonances will also have an effect on the circuit performance.

Fig.5 shows the S-parameters of the same straight open-end stub with air-bridges. As it can be seen, the stub resonates at nearly 24.5 GHz where the length of the stub is approximately quarter of a coplanar mode wavelength. It can be noticed that the agreement between the theoretical and experimental data in Fig.5 is much better than the one seen in Fig.4. This can be attributed to the fact that the air-bridges tend to prevent the slotline mode from being excited in the CPW stubs which effectively reduces radiation losses. In addition, it can be seen that the resonance effect noticed in Fig.4 has disappeared since X_3 is shorted by the relatively small air-bridge inductance L_a. Alternatively, the air-bridges short out the slotline mode, thus, eliminating interaction with the cavity resonances. As a result, with the presence of air-bridges, cavity resonances have no effect on the characteristics of a straight stub as long as it is placed symmetrically inside the cavity. One can also notice an anomalous effect at 40 GHz existing in Fig.5. A similar effect has been found in [4] for the case of a bent open-end stub. This effect may be due to a resonating slotline mode excited in the stubs beyond the air-bridge.

Fig.6 shows $Mag(S_{12})$ for the bent open-end CPW stub (Fig.2b) of mean length $1100\,\mu m$ with and without air-bridges. In this case, the width of the cavity is taken to be $2\,mm$. It can be seen that for the bent stub without air-bridges, the agreement between theory and experiment is better than that seen in fig.4 for the straight stub without air-bridges. The same behavior, observed in the straight open-end stubs with air-bridges at 40 GHz, can be seen more clearly in Fig.6 for the bent stubs with air-bridges. Moreover, the resonant frequency of this bent stub with air-bridges is approximately the same as the one for the straight stub of the same mean length.

From the measured scattering parameters, the loss factor due to the stubs can be calculated. This loss factor includes radiation, conductor, and dielectric losses. Since the stubs are all the same length, a comparison of the loss factor can provide a measure of the radiation loss. Fig.7a shows the loss factor of the open-end stubs without air-bridges. It is noticed that loss is maximum at the resonant frequency of the stubs, which is similar to what has been found in microstrip stubs [8]. Furthermore, the loss factor for the straight stub is larger than that for the bent stub. Lower loss is due to the fact that in the case of bent stubs, the fields radiated by the slotline modes in the two opposing stubs partially cancel. This explains why the agreement between the theoretical and experimental results for the bent stubs without air-bridges (Fig.6) is better than that for the straight stubs without air-bridges (Fig.4). The loss factor for the open-end stubs with air-bridges is shown in Fig.7b. The air-bridges reduce radiation loss by shorting out the coupled slotline mode, but it is still noted that the straight stub have increasing radiation loss after the first resonant frequency.

Numerical and experimental results for the short-end stubs (Figures 2c and 2d) will be presented in the symposium.

CONCLUSIONS

A comprehensive theoretical and experimental study of CPW shunt stubs has been presented. In the theoretical analysis, the CPW was assumed to be inside a cavity, while, the experiments were performed in an open environment. A hybrid technique has been developed to analyze the CPW discontinuities which proved valid since the results obtained theoretically and experimentally agreed very well. In addition, the effect of the cavity resonances on the behavior of the stubs has been studied. It was found that air-bridges suppress the slotline mode and cancel the effect of the cavity resonances on the characteristics of the stub. Moreover, It has been shown through experiments that bent CPW stubs should be used whenever the circuit layout permits to reduce the radiation loss caused by the parasitic coupled slotline mode.

ACKNOWLEDGMENT

The theoretical work was supported by the National Science Foundation under contract ECS-8657951.

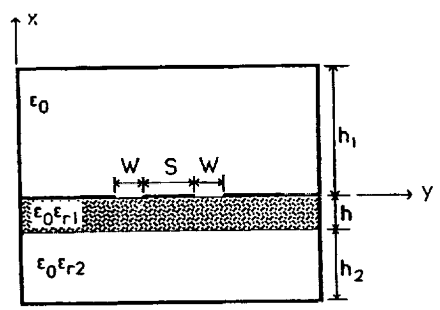

Figure 1: A cross section of a CPW inside a cavity.

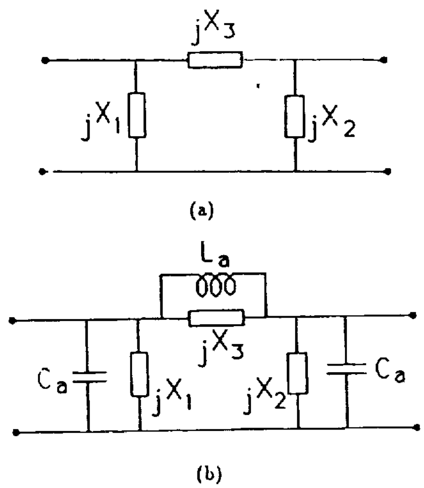

Figure 3: (a) Equivalent circuit of the CPW discontinuities shown in Fig.2 without the air-bridges. (b) The modified equivalent circuit after taking the air-bridges into consideration. (The reference planes are taken at the end of the uniform feeding lines)

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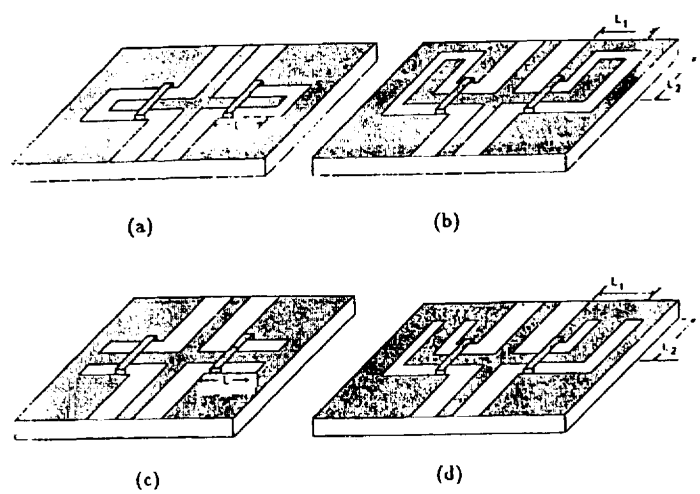


Figure 2: Different CPW shunt stubs. (a) Straight open-end CPW stub. (b) Bent open-end CPW stub. (c) Straight short-end CPW stub. (d) Bent short-end CPW stub.

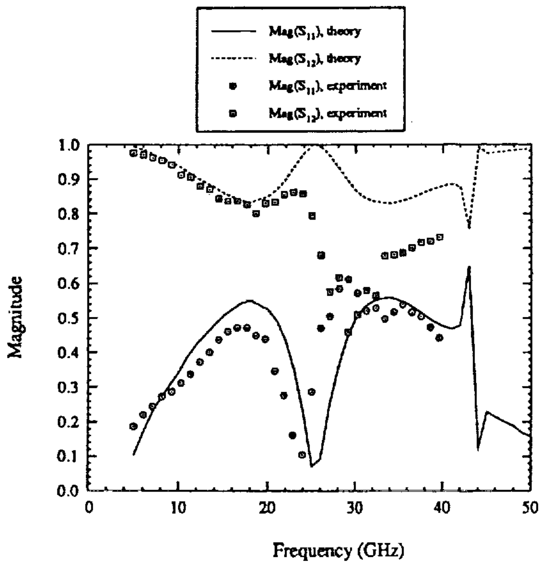


Figure 4: Scattering parameters of the straight open-end stub without air-bridges with $L = 1100\mu m$.

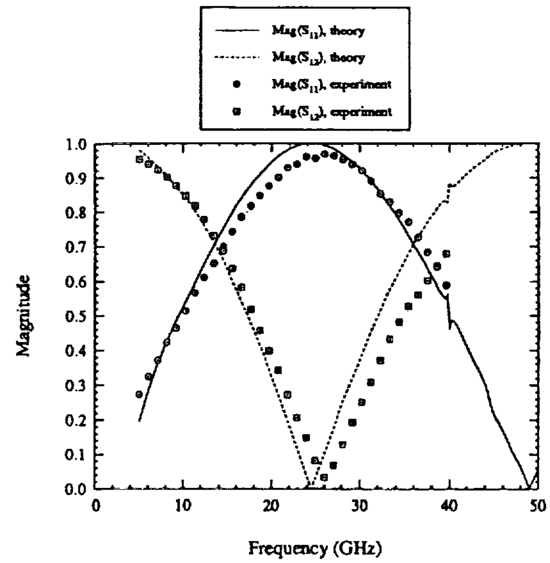


Figure 5: Scattering parameters of the straight open-end stub with air-bridges with $L = 1100\mu m$.

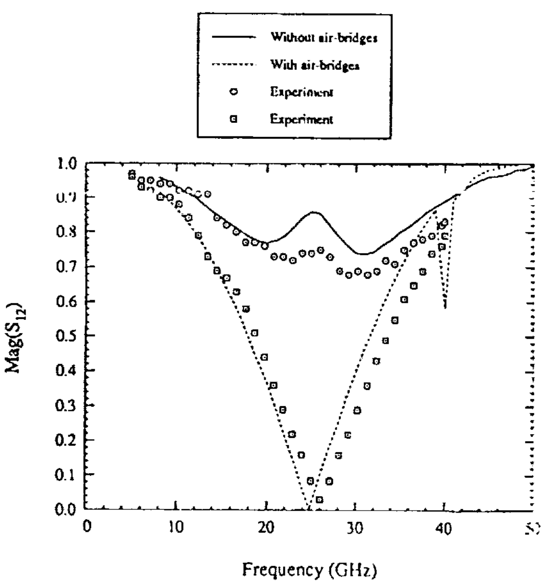
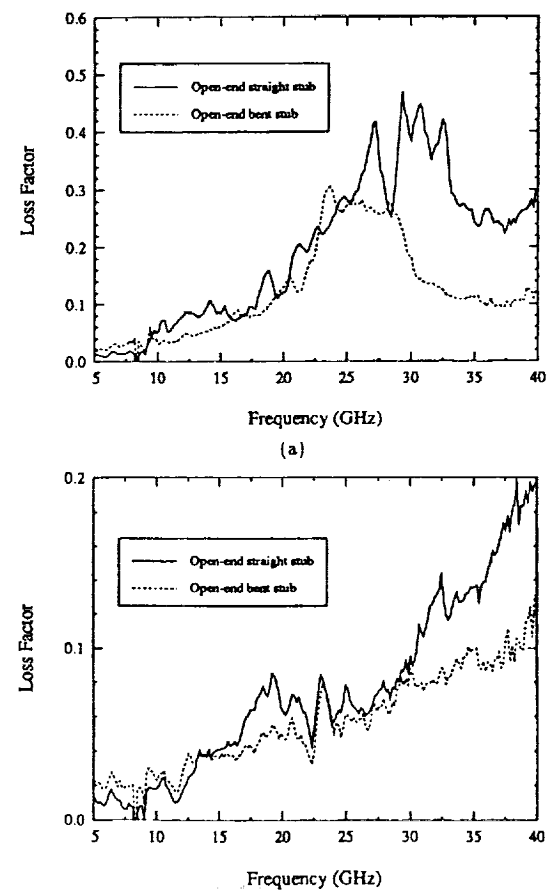


Figure 6: $Mag(S_{12})$ of the bent open-end stub with and without air-bridges with mean length of $1100\mu m$ ($L_1 = 100\mu m$, $L_2 = 1025\mu m$)



(b)

Figure 7: The measured loss factor of the open-end CPW stubs (a) without air-bridges. (b) with air-bridges.