# Realistic Equivalent Circuit Model of Coplanar Waveguide Open Circuit: Lossy Shunt Resonator Network

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***Abstract*—Realistic equivalent circuit model of coplanar waveguide (CPW) open circuit is proposed and formulated as a lossy shunt resonator network based on the fact that the electromagnetic (EM) wave propagates at the transverse direction around the open-end. A "short-open calibration" (SOC) technique is applied in the fullwave method of moments (MoM) to effectively extract all the model parameters over a wide frequency range. After the extracted capacitance at low frequency is confirmed by the previous static results, extensive investigation is implemented to reveal the high-frequency dynamic features of CPW open circuit, e.g., shunt resonance and radiation loss. A CPW open-end circuit is then fabricated and measured to provide an experimental verification on the proposed model.**

***Index Terms*—Coplanar waveguide, equivalent circuit model, method of moments, open-end circuit, parameter extraction and short-open calibration.**

## I. Introduction

COPLANAR waveguide (CPW) has gained an increasingly wide application in the development of microwave and millimeter-wave integrated circuits (MMICs) because of its attractive features [1], such as being easy to insert the device in shunt or series form and low frequency dispersion. In the past decades, extensive research has been undertaken to characterize a variety of CPW circuits and/or discontinuities using the theoretical and experimental techniques [2]–[7]. The fullwave method of moments (MoM) [2], [7] has been found as one of most efficient and effective numerical algorithms in the electromagnetic (EM) simulation of the overall CPW circuit layout with complex configuration. Nevertheless, the MoM itself has its unique capacity in the physical demonstration of all the dynamic EM behaviors, such as frequency dispersion and radiation loss. However, very few effort has been made today to address one of most challenging issues, that is, effective extraction of equivalent circuit models for basic CPW elements, such as open, short, bend, T-junction and so on, from the fullwave EM simulation.

To meet this requirement, a representative example is taken here for the characterization of a simple CPW open-end circuit and the formulation of its general-purpose dynamic circuit model. So far, much effort was made to derive its open end static capacitance by using the experimental direct calibration [3] and indirect resonance procedures [6], static variational technique [6], and finite element method (FEM) [4] as well as the full-wave FEM [5]. As the frequency increases, however, such a static capacitance model absolutely becomes very approximate in theory, especially for CPW with wide strip width. Different from the case of microstrip open-end, the CPW open-end should be considered as a transversely oriented slotline section or slot resonator, since a partial amount of EM fields propagate forward and backward along the transverse direction. In this work, a "short-open calibration" (SOC) technique [8] is applied to de-embed or extract such a dynamic circuit model from the determinant MoM algorithm [9]. After the SOC-extracted parameters at low frequency are confirmed by the static ones, detailed results are provided to demonstrate the realistic dynamic model of CPW open circuit over a wide frequency range. At last, a CPW circuit sample is fabricated to provide an experimental verification on the proposed model.

## II. Realistic Circuit Model

Fig. 1(b) describes the physical layout for fullwave MoM characterization of a CPW open circuit, which is driven by the CPW feeding line. Different from the case of microstrip circuit as in [8], [9], an impressed electric current source is introduced at the central plane (P) of the port location, far away from the core open-end, to the formulation of a source-type magnetic field integral equation (MFIE), similarly to the modeling of shielded CPW discontinuity [9]. By applying the Galerkin's technique, the equivalent magnetic current density over the whole slot area can be numerically solved as a response of the impressed current, thereby deriving explicitly the input impedance or admittance at the port. Looking at the left-side part in Fig. 1(b). The impressed field provides an approximate representation of the field distribution of the dominant CPW mode at the port location. To calibrate this parasitic effect called "port discontinuity" [8], the whole CPW layout is at first divided into two distinct parts: error box and core open-end circuit model, as illustrated in Fig. 1(c) in the format of an equivalent network topology. As detailed in [8], the former error box represents not only the port discontinuity described above, but also the actual behavior of the uniform CPW line in the MoM scheme. This error box can be well characterized through the definition of two calibration elements, ideal CPW short and open circuits [7], in the MoM. They can be formulated by terminating vertically the perfectly electric and magnetic walls, respectively, at the reference plane (R) in Fig. 1(b). As a

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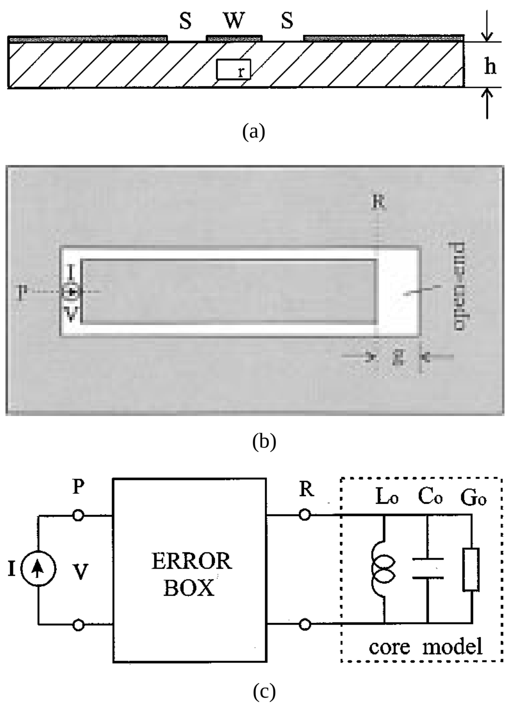



Fig. 1. Physical layout and equivalent topology arranged for fullwave MoM-based derivation of realistic circuit model of a CPW open-end circuit: (a) CPW cross-section; (b) physical layout; and (c) equivalent topology.

result, the core circuit model with the parameter of a complex admittance ($Y_o = G_o + jB_o$) can be explicitly extracted after such an error box is evaluated in the MoM and then removed out based on the cascaded circuit network as depicted in Fig. 1(c).

In the following, detailed results are provided to demonstrate the extracted circuit model parameters of the CPW open-end circuit. First of all, our obtained results at low frequency show us that the radiation-oriented conductance ($G_o$) appears negligibly small and the susceptance ($B_o$) tends to increment as a linear function of the frequency, thereby exhibiting the behavior of an equivalent lumped-element capacitance ($C_o$). Fig. 2 depicts the extracted capacitance ($C_o$) versus the normalized gap width ($g/h$) at the open-end together with the results obtained from the static variational technique [6] and static FEM [4]. All three sets of results appear the consistently unchanged variation in such a way that the $C_o$ falls down and then gradually converges to the unchanged values as the gap width ($g$) is enlarged. Our attention is now shifted to the investigation on the realistic dynamic circuit model of such a CPW open circuit over a wide frequency range. Fig. 3(a) shows the extracted complex open-end admittance ($G_o + jB_o$) under the choice of three different strip widths ($W$). It can be seen from Fig. 3(a) that $G_o$ is extremely small at the beginning, tends to rapidly rise up, and then go down as the frequency increases, while $B_o$ increments at first and falls down from the positive to the negative value, thus exhibiting the lossy resonance behavior of such an unbounded CPW open-end. Otherwise, the resonant frequency is found to shift downward as $W$ is widened and the lossy $G_o$ is kept almost unchanged regardless of narrow or wide $W$. Fig. 3(b) depicts the relevant parameters under the different gap widths ($g$), indicating that the resonant frequency is almost stationary around 16.0–17.0 GHz and the conductance $G_o$ goes down rapidly as

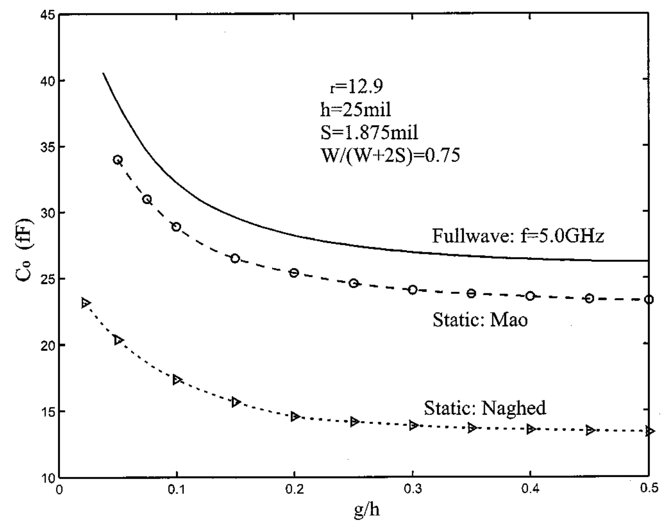



Fig. 2. SOC-extracted quasistatic CPW open-end capacitance against those from the static techniques.

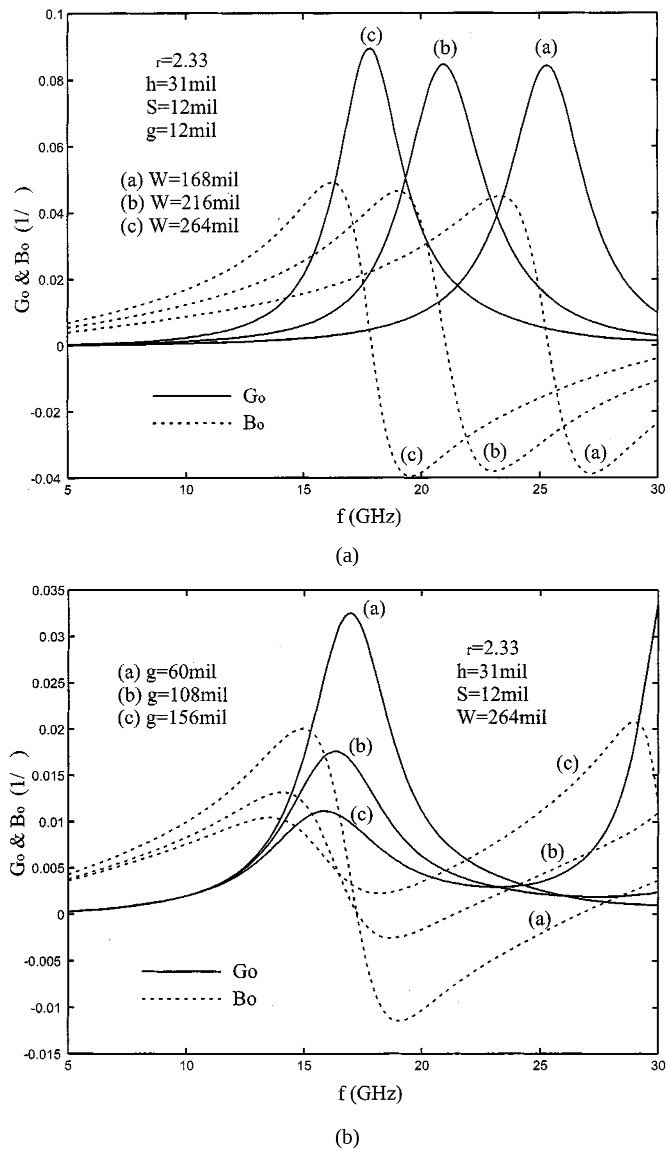
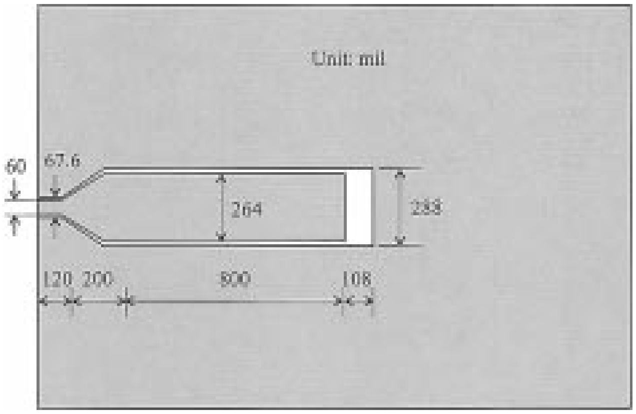
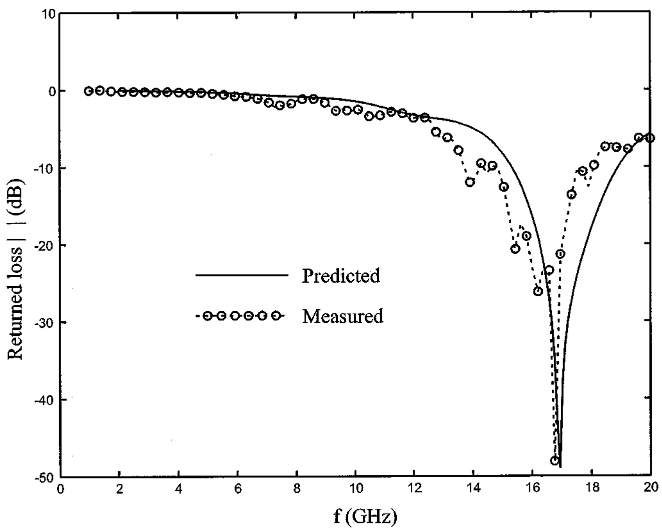



Fig. 3. Frequency-distributed open-end admittance ($Y_o = G_o + jB_o$) versus strip width ($W$) and gap width ($g$) for CPW open circuits. (a) S trip width ($W$) and (b) gap width ($g$).




(a)




(b)

Fig. 4. Predicted and measured results of a CPW open-end circuit sample. (a) CPW circuit layout and (b) returned loss ($|\Gamma|$).

the width ($g$) increases. These results suggest to us that the total slot length ($W + 2S$) determines the resonant frequency and the gap or slot width ($g$) contributes to the radiation conductance ($G_o$) for such an open-end slot radiator.

## III. Experimental Verification

In this section, a CPW open-end circuit is characterized, fabricated and measured to provide a preliminary support on the effectiveness and accurateness of the above-discussed dynamic circuit model. Fig. 4(a) describes the top-view of this circuit layout, in which a CPW open-end is driven by a nonuniform CPW feeding line with the unchanged characteristic impedance in order to be linked to the external coaxial cable. Fig. 4(b) depicts the relevant predicted and measured return loss at the coaxial-to-CPW interface over a wide frequency range (1.0 to 20.0 GHz). The predicted results are obtained on a basis of the cascaded circuit topology, in which the open-end is considered as a GLC network with the parameters as shown in Fig. 3(b) and the CPW feeding line is modeled as a nonuniform transmission line with the parameters from the closed-form formula [1]. Meanwhile, the measured resulted are derived with the use of a simple full-port calibration procedure. It can be observed from Fig. 4(b) that both them are in good agreement with each other over a wide band. The returned loss ($|\Gamma|$) appears very small at the frequency lower than 8.0 GHz, starts to fall down in an accelerated speed toward the minimum value, and at final rises up again. These results reflect well the frequency response of a CPW-fed slot radiator [10], in which the bandwidth achieves wider than 10.0% and the maximum ($|\Gamma|$) is about 40 dB at the central frequency ($f = 17.0$ GHz).

## IV. Conclusion

In this work, a general-purpose realistic equivalent circuit model is presented and formulated for the first time to the characterization of a CPW open-end circuit over a wide frequency range. Through the SOC calibration technique, the dynamic model parameters are effectively extracted from the fullwave MoM simulation. The detailed results show us that the CPW open-end may be reasonably perceived as a static capacitance at low frequency but has to be strictly considered as a dynamic lossy GLC-resonator network at high frequency. After the obtained parameter is confirmed by the two static techniques, a CPW open-end circuit sample is fabricated and measured to provide an evidently experimental verification on the proposed realistic dynamic model.

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