Unified 3-D Definition of CPW- and CSL-Mode Characteristic Impedances of Coplanar Waveguide Using MOM-SOC Technique

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***Abstract*—Characteristic impedances of two dominant modes, even CPW- and odd CSL-mode, in the coplanar waveguide (CPW) are defined and characterized with resorting to the network equivalence of a finitely extended CPW line in a three-dimensional (3-D) method of moments (MoM) platform. By introducing the port model with a pair of even or odd symmetrical current sources, a determinant MoM scheme is at first formulated to establish the explicit relationship among the port currents and voltages. A short-open calibration (SOC) technique is then accommodated in this MoM to remove the parasitic port discontinuity effects. Our results are compared with those of the two-dimensional (2-D) definition and demonstrate for the first time the equivalent 3-D characteristic impedances of both CPW- and CSL-mode.**

***Index Terms*—Characteristic impedance, coplanar waveguide, CPW-mode, CSL-mode, method of moments, short-open calibration.**

I. INTRODUCTION

CHARACTERISTIC impedance of a planar transmission line [1] has been commonly used as a fundamental circuit parameter in the design of today's high-frequency integrated circuits. Its definition is usually carried out in terms of the transverse field quantities from a two-dimensional (2-D) numerical calculation under the quasi-TEM assumption. A called TEM equivalent characteristic impedance of a microstrip line was originally introduced in [2] and has been extensively investigated [3]–[5] via three-dimensional (3-D) method of moments (MoM) together with numerical de-embedding techniques. This 3-D definition not only allows eliminating the ambiguity of three different 2-D definitions [1] at high frequency, but also permits a direct and absolute comparison between simulated and measured characteristic impedances as concluded in [4].

In contrary, coplanar waveguide (CPW) has also been gaining a wide application in microwave and millimeter integrated circuits (MMICs). Due to the existence of three separate conductors, the unwanted coupled-slotline (CSL) mode may be excited in any asymmetrical CPW structure, for instance, CPW bend [7], and propagates together with the dominant CPW-mode. To meet the need in modeling a variety of CPW circuits and suppressing the harmful mode-conversion at an asymmetrical CPW geometry, it is a critical issue to effectively define the relevant two characteristic impedances with regarding to even CPW- and odd CSL-mode. Unfortunately, very little work has been done to investigate these two characteristic impedances except the 2-D TEM-mode voltage-power definition [8]. The authors in [7] tried to directly de-embed the 3-D impedance from the MoM simulation, but eventually failed to achieve stable results.

This work aims at unified 3-D definition of characteristic impedances of these CPW- and odd CSL-mode characteristic impedances via our developed hybrid method of moments (MoM) and short-open calibration (SOC) technique [6], named by "MoM-SOC." In this case, a finitely extended CPW line section is at first modeled in terms of the 3-D MoM scheme and its transmission parameters, such as characteristic impedance and effective dielectric constant, are then extracted relying on the ideal CPW short and open standards [9] in the self-consistent MoM. Extensive results originally exhibit their frequency-dependent electrical behaviors and are then validated by only available 2-D results [8].

II. CPW- AND CSL-MODE CHARACTERISTIC IMPEDANCES

Fig. 1(a) depicts the physical layout with three cascaded CPW line sections arranged for unified 3-D definition of both CPW- and CSL-mode characteristic impedances using our MoM-SOC technique. The left- and right-side CPW feeding lines are simultaneously driven by a pair of longitudinal current sources in order to formulate a determinant admittance-type MoM scheme. By enforcing that $I_{1a} = I_{1b}$ and $I_{2a} = I_{2b}$, the CPW-mode and other high-order even modes may be excited. As the line length (L_s) is selected electrically long, however, only the CPW-mode can reach to the uniform CPW line section with the two terminals, i.e., R_1 and R_2. Fig. 1(b) denotes the relevant equivalent network, in which the two feeding lines are modeled as the two identical error boxes [6] while the uniform central CPW is perceived as a CPW-mode transmission line with the unknown characteristic impedance (Z_0^{CPW}) and effective dielectric constant ($\varepsilon_{re}^{\mathrm{CPW}}$).

The error box here comprises a two-port network ($[X_E]$) and shunt admittance ($2Y_{\Delta}$), and its overall network parameters can be self-consistently derived relying on the two SOC calibration standards [6], i.e., ideal CPW-mode short and open elements [9]. As a result, the CPW-mode transmission line network parameters can be effectively extracted and expressed here as a two-port

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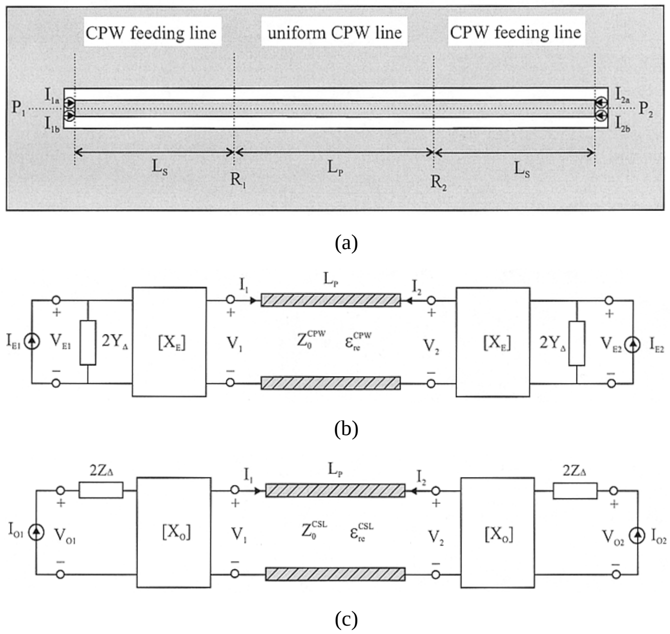

Fig. 1. Physical layout and equivalent transmission line network for unified 3-D definition of CPW- and CSL-mode transmission parameters of coplanar waveguide using fullwave MoM-SOC technique. (a) Physical layout; (b) equivalent network for CPW-mode; and (c) equivalent network for CSL-mode.

ABCD-matrix with the elements of $A^{\rm CPW}$, $B^{\rm CPW}$, $C^{\rm CPW}$, and $D^{\rm CPW}$ such that

$$Z_0^{\rm CPW} = \sqrt{\frac{B^{\rm CPW}}{C^{\rm CPW}}} \tag{1}$$

$$\varepsilon_{re}^{\rm CPW} = \left[\frac{c}{\omega L_p}\left(n\pi + \tan^{-1}\sqrt{\left|\frac{B^{\rm CPW}C^{\rm CPW}}{A^{\rm CPW}D^{\rm CPW}}\right|}\right)\right]^2 \tag{2}$$

in which c is the light velocity and n is the integer number. Very similarly, the characteristic impedance ($Z_0^{\rm CSL}$) and effective dielectric constant ($\varepsilon_{re}^{\rm CSL}$) of the odd CSL-mode can be also characterized using the above MoM-SOC under the odd excitation at the CPW feeding ports, i.e., $I_{1a} = -I_{1b}$ and $I_{2a} = -I_{2b}$. Fig. 1(c) illustrates its equivalent network topology in which each feeding line section is perceived as an alternative error box with the circuit network ($[X_O]$) and series impedance ($2Z_\Delta$). In Fig. 1(b) and (c), Y_Δ and Z_Δ are attributed to the offset distance (Δ) of our selection between the impressed current source and the symmetrical location at each port under the even and odd excitation, respectively.

III. Results and Verification

Now, the above MoM-SOC technique is executed to de-embed and extract the CPW- and CSL-mode transmission parameters of a finitely extended CPW line over a wide frequency range. Fig. 2(a) and (b) depict the calculated effective dielectric constants and characteristic impedances of a uniform CPW line with the fixed length of $L_p = 250$ mil under three different feeding line lengths (L_s). Here, the transverse mesh size is kept 5 mil while the longitudinal counterpart is selected as 5, 10, and 15 mil with regarding to $L_s = 125$, 250, and 375 mil, respectively. First of all, all the parameters are observed here to consistently converge to their relevant smoothly varied curves (solid

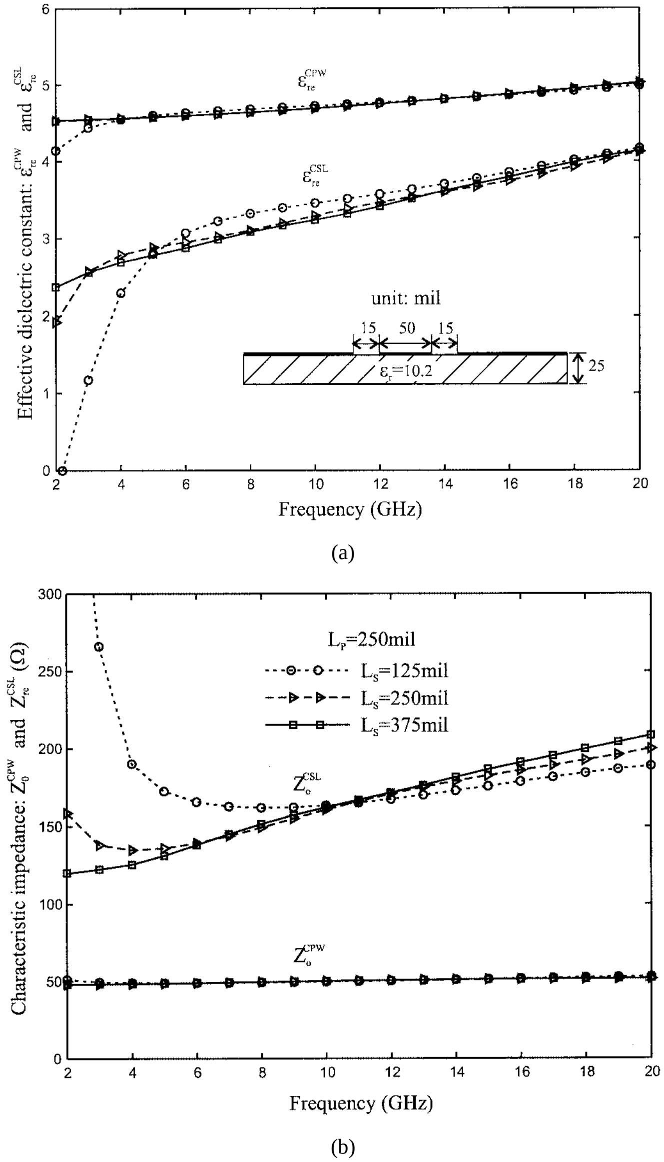

Fig. 2. Convergence behaviors of the SOC-extracted CPW- and CSL-mode transmission parameters with respect to different feeding line lengths (L_s). (a) Effective dielectric constant ($\varepsilon_{re}^{\rm CPW}$ and $\varepsilon_{re}^{\rm CSL}$) and (b) characteristic impedance ($Z_0^{\rm CPW}$ and $Z_0^{\rm CSL}$).

lines), especially at low frequency, as L_s is stretched to 375 mil. Meanwhile, they appear to gradually rise up with frequency, thus exhibiting their frequency dispersion behaviors in a layered structure. Further, $\varepsilon_{re}^{\rm CSL}$ is found always lower than $\varepsilon_{re}^{\rm CPW}$, indicating us that the wavelength of CSL-mode is longer than that of CPW-mode at the same frequency. It is the reason why the longer L_s should be usually selected in the accurate modeling of the CSL-mode related electrical behaviors in CPW discontinuities. As the frequency increases from 2.0 to 20.0 GHz, $Z_0^{\rm CPW}$ tends to be almost unchanged at the 48.5 Ω while $Z_0^{\rm CSL}$ significantly goes up from about 120 to 200 Ω. It is basically attributed to the fundamental dissimilarity between the CPW-mode and CSL-mode propagation performances along the uniform CPW line, i.e., quasi-TEM and non-TEM natures.

To validate the above-derived transmission parameters, our newly derived 3-D MoM-SOC results are plotted in Fig. 3(a) and (b) together with those obtained from the 2-D MoM technique

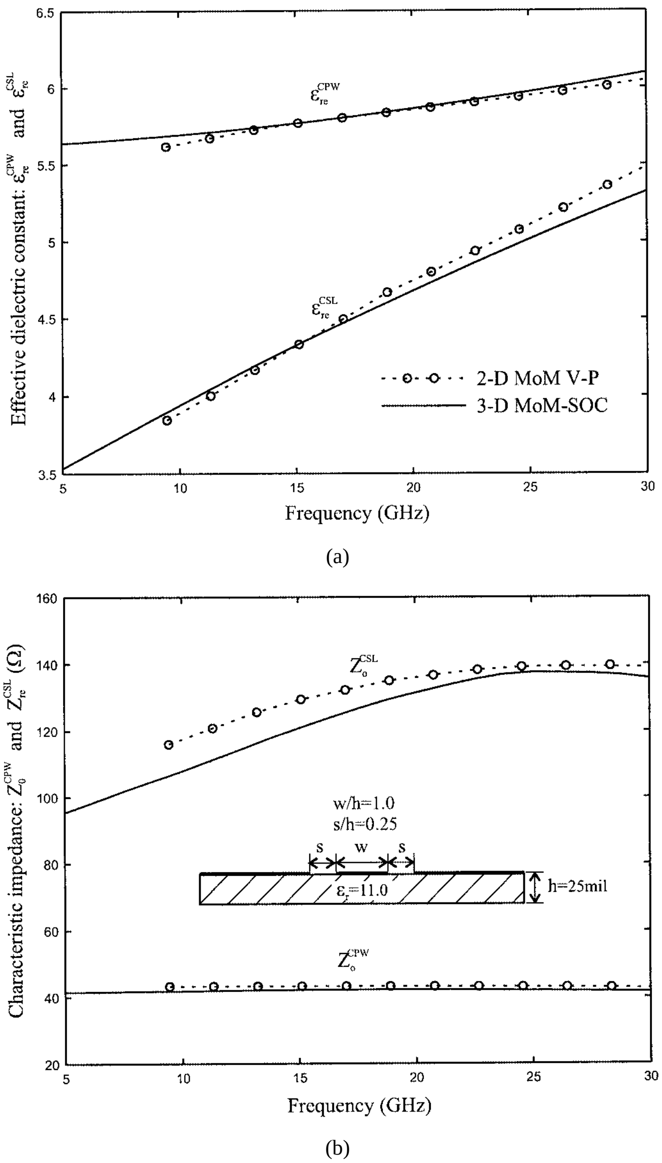

Fig. 3. Comparison among the SOC-extracted CPW- and CSL-mode transmission parameters and those from the 2-D MoM technique in [8]. (a) Effective dielectric constant ($\varepsilon_{re}^{\mathrm{CPW}}$ and $\varepsilon_{re}^{\mathrm{CSL}}$) and (b) characteristic impedance (Z_0^{CPW} and Z_0^{CSL}).

[8]. It can be seen in Fig. 3(a) that both $\varepsilon_{re}^{\mathrm{CPW}}$ and $\varepsilon_{re}^{\mathrm{CSL}}$ are in excellent agreement with each other and they increment as a quasi-linear function of frequency over the range of 5.0 to 30.0 GHz. Also, as depicted in Fig. 3(b), our 3-D defined Z_0^{CPW} is found the almost same as the 2-D Z_0^{CPW} while the 3-D Z_0^{CSL} is reasonably close to the 2-D Z_0^{CSL} under the voltage-power definition [8]. As pointed out in [7], there is no unanimous definition of CSL-mode characteristic impedance due to its non-TEM nature [7]. However, it has been well examined here through our unified 3-D MoM-SOC technique that the voltage-power definition is more suitable for both CPW- and CSL-mode characteristic impedance.

IV. Conclusions

A fullwave MoM-SOC technique is applied here to unified 3-D definition of characteristic impedances of two propagation modes, i.e., CPW- and CSL-mode, in the uniform CPW line with finitely extended length. Our derived results for the first time demonstrate the 3-D transmission parameters of both dominant modes and also are well validated by their 2-D counterparts. This 3-D definition not only helps us to clear the ambiguity of CPW- and CSL-mode characteristic impedances, and also allows us to characterize and measure the multi-mode circuit performance of CPW structures/circuits with complex configurations based on the same characteristic impedance standards [4].

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