De-Embedding Slotline Propagation Parameters

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***Abstract*—A new method for extracting the slotline propagation constants is presented. The test structure consists of coplanar access lines, coplanar-slotline transitions, and the slotline to be measured. Since no special mathematical computations are needed, the method may be directly implemented using commercially available microwave CAD packages. The method may be applied up to millimeter-wave wavelengths. The experimental results are compared to electromagnetic simulations.**

I. Introduction

VERY LITTLE experimental data [1] have been published until now on the slotline propagation parameters extraction (characteristic impedance Z_{car} and propagation constant γ). The main difficulty in the experimental characterization is due to the slotline structure itself; it requires the use of both uncommon "ground-signal" probe tips [2] and precision slotline on-wafer calibration standards unless a de-embedding technique is used. Microstrip or coaxial-launching slotline structures may be designed, but they suffer from poor performances and fail at high frequencies.

In this letter, we propose a new de-embedding technique for determinating slotline propagation parameters. The method uses usual "ground-signal-ground" probe tips (usually called "coplanar" probe tips) for on-wafer measurements, a standard calibration procedure, and it is suitable for slotline characterization in the millimeter-wave range.

II. The Principle of the Method

The test structure is shown in Fig. 1. Basically, it consists of two back-to-back coplanar-slot transitions [3]. Access lines are 50-Ω coplanar waveguides (CPW's). The slotline length is 1. A previous TRL calibration using coplanar standards is necessary, fixing the measurement reference planes A-A', and B-B'. We use the propagation constants model [4] for the slotline. The slotline $\mathbf{ABCD}$ matrix is

$$ABCD = \begin{bmatrix} \cosh\gamma l & Z_{\mathrm{car}}\sinh\gamma l \\ Y_{\mathrm{car}}\sinh\gamma l & \cosh\gamma l \end{bmatrix} \tag{1}$$

Exterior access CPW's slots do not see open circuits, but instead an unknown complex impedance Z_{ap}, which is due to aperture radiation. Taking this into account, the electrical circuit between the planes A-A' and B-B' is a π-bridge (Fig. 2). Its $ABCD$ matrix is shown in (2), at the bottom of the next page.

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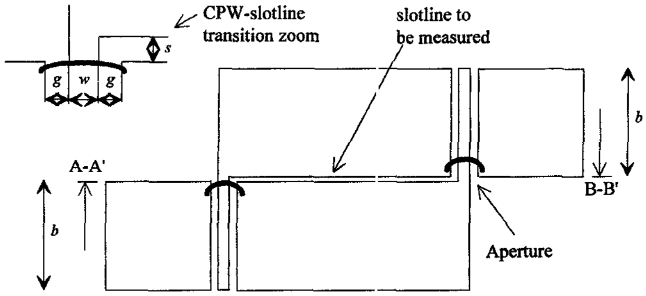

Fig. 1. Slotline de-embedding structure lay-out.

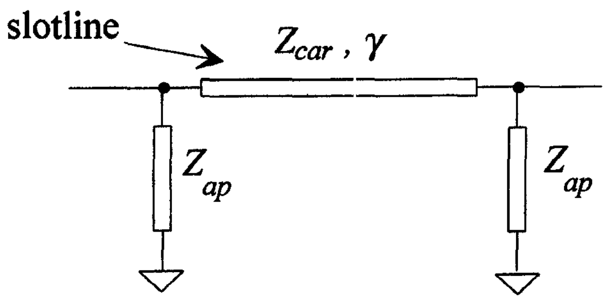

Fig. 2. Slotline de-embedding structure equivalent circuit.

One may notice that the parameter $\mathbf{B}$ is independent of the aperture impedance Z_{ap}. Consider now two structures (Fig. 1) having two different slotline lengths l_1 and l_2. By dividing the corresponding $\mathbf{B}$ parameters one obtains:

$$\frac{B_1}{B_2} = \frac{\sinh\gamma l_1}{\sinh\gamma l_2} \tag{3}$$

Equation (3) allows for determinating γ. The characteristic impedance may be readily computed in the next step:

$$Z_{\mathrm{car}} = \frac{B_i}{\sinh\gamma l_i}, \quad i = \overline{1,2} \tag{4}$$

We may resume the de-embedding sequence as follows:

- creating two structures (Fig. 1) having two slotline lengths l_1 and l_2
- TRL calibration
- matrices transformation s → $\mathbf{ABCD}$
- determinating γ, (3)
- determinating Z_{car}, (4)

III. Specific Problems

Lengths l_1 and l_2 are chosen taking into account the measurement frequency range. The condition is that the two slotlines lengths significantly differ from $n\lambda/2$, $n = 0, 1, \ldots,$ [5]. We took the practical criteria: $\theta_1(f_{\min}) > 20°$, $\theta_2(f_{\max}) <$

160°, where $\theta_i(f)$ is the electrical length of the slotline l_i at the frequency f.

It is important to ensure a good rejection of the even, "coupled slotlines" mode on the access CPW's. This is achieved using air-bridges. Since the air-bridge inductance is proportional with its length, in order to ensure a proper short-circuit between the CPW's ground planes, the CPW's should be kept narrow (i.e., $w + 2g$ small). The best is to use thin film air-bridges or to put several in parallel if bonding wires are used.

Having narrow CPW's also presents the advantage of keeping the slot bend discontinuity small. In a first approximation, the discontinuity may be neglected. However, if it has to be taken into account, we suggest a straightforward method. We model the discontinuity as a slotline overlength Δl. Δl may be determined from low-frequency measurements, where $\sinh\gamma \cong \gamma$ and the right term of (3) is independent of γ. We found experimentally that $\Delta l \cong g + s$.

IV. Experimental Results

Test structures have been built on alumina substrate ($\varepsilon_r = 9.9$, $h = 254$ μm, metal thickness $= 4$ μm). The 50-Ω access CPW's ($w = 50$ μm, $g = 30$ μm) have a length of 540 μm. Slotlines having four different gaps have been tested: $s = 20$, 30, 40, and 60 μm. The two slotlines lengths were $l_1 = 800$ μm and $l_2 = 1500$ μm. Slotlines lateral planes widths are $b = 540$ μm. The frequency range is 10–30 GHz. The transcendent (3) has been solved with a precision of 2.5% by starting from an appropriate expression of γ and by adding correction terms. In order to check the results, one should verify that the two characteristic impedances obtained for the two slotline lengths are equal. In our case, this happens with a precision better than 2%. The absolute values of the characteristic impedance imaginary parts are inferior, for all the cases, to 6 Ω. The propagation constants have been also computed with a commercial software package (LINMIC + /N, from Jansen Microwave), that uses the spectral operator expansion technique [6]. In Fig. 3(a) and (b), a comparison between our measurements and LINMIC + /N simulations is presented. Very good agreement is observed. The measurements are also compared with propagation parameters computed using Cohn's method ([7], Fig. 3(a) and (b), $s = 60$ μm). This method neglects the metallization thickness and the slotline lateral planes' widths. Significant differences have been observed. It is therefore essential when simulating slotlines in the millimeter-wave range to take into account both the lateral planes' metallization thickness and width.

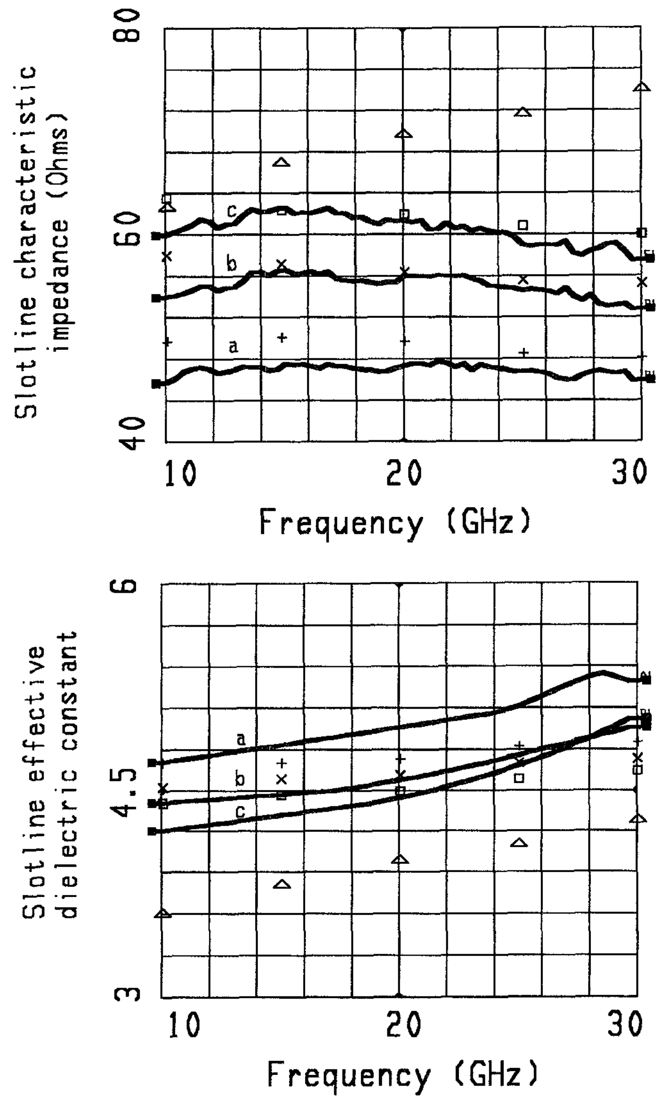

Fig. 3. Measured (solid lines—a: $s = 20$ μm; b: $s = 40$ μm; and c: $s = 60$ μm) and simulated (LINMIC+/N: +: $s = 20$ μm; ×: $s = 40$ μm; □: $s = 60$ μm; Cohn's results [7]: △: $s = 60$ μm) slotline propagation parameters. The slotline lateral planes width is $b = 540$ μm. The substrate is alumina ($\varepsilon_r = 9.9$, $h = 254$ μm), and the metallization thickness is 4 μm.

V. Conclusion

A novel method for extracting slotline propagation parameters is presented. The method uses standard probe tips and a TRL calibration procedure. It may be used both in low microwave frequency ranges and at millimeter-wave frequencies. The simplicity of the technique allows for a direct implementation on a microwave CAD package such as MDS (Hewlett-Packard). As a secondary result, the aperture impedance may also be determined. We demonstrated the method in the frequency range 10–30 GHz. A comparison with theoretical predictions is done, and good agreement is observed.

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$$ABCD = \begin{bmatrix} \cosh\gamma l + Y_{\text{ap}} Z_{\text{car}} \sinh\gamma l & Z_{\text{car}} \sinh\gamma l \\ (Y_{\text{ap}}^2 Z_{\text{car}} + Y_{\text{car}}) \sinh\gamma l + 2Y_{\text{ap}} \cosh\gamma l & Y_{\text{ap}} Z_{\text{car}} \sinh\gamma l + \cosh\gamma l \end{bmatrix} \quad (2)$$

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