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A Method for On-Wafer Experimental Characterization of a 4-Port Circuit, Using a 2-Port Vector Network Analyzer

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Abstract. The paper presents an experimental method useful to characterize on-wafer a four-port circuit, using a two-port VNA (Vector Network Analyzer). As an example, the method is applied for a coupler. The results obtained by using this method and the expected results obtained by simulation are in good agreement.

Key words: Vector network analyzer, on-wafer measurement, scattering matrices, CRLH coupler.

1. Introduction

Due to the requirements for compact size microwave circuits, more and more parts of complex microwave circuits are monolithically integrated together, on the same semiconductor substrate. In this context, many microwave devices are experimented on semiconductor substrate, the experimental characterization being performed by using on-wafer technique. For two-port circuits, a two-port VNA (Vector Network Analyzer) may be successfully used. For multi-port circuits, like MEMS (Micro-Electro-Mechanical System) matrices, directional couplers, power dividers and so on (see for example [1] – [4]), the all scattering parameters cannot be obtained simultaneously, by using a two-port VNA.

The experimental characterization of microwave multi-port circuits could be made by using a two-port VNA based connectors, by matching the other $n-2$ ports to 50 Ω, where n is the number of ports. This solution may be easily applied for hybrid circuits.

For MMICs (Monolithic Microwave Integrated Circuits), a characterization method using a two-port VNA based connectors is not longer a comfortable solution because of mechanical test fixtures which must be realized (useful for experimental characterization only). Therefore, on-wafer solutions must be developed.

One way for on-wafer characterization of multi-port circuits is to realize a set of circuits, each one having $n-2$ ports ended on 50 Ω thin-film resistors (see [3], for example). Unfortunately, this technique is not more accurately because for these loads connected to the $n-2$ ports, the frequency behaviour, but also the impedance value to a particular frequency, cannot be known accurately.

In this paper, it is proposed an experimental characterization method for a four-port circuit, using a two-port VNA, when the other ports are let open. For this method, successive re-normalization of the circuit scattering parameters matrix is performed, computing also the load reflection coefficients for the open-ended ports. A method based on re-normalization technique may be found in [5] (see also [6]), where the load impedances connected to the ports are different from 50 Ω, but the ports which are not connected to the VNA ports are not let open.

The method is applied for a coupler (designed in [7]) consisting of two coupled CRLH (Composite Right/Left-Handed) TL (Transmission Lines), showing a good agreement between the experimental results and the expected ones, obtained by simulation.

2. Method description

The proposed method to characterize a circuit having n ports consists of $m = C_n^2 = \dfrac{n!}{2!(n-2)!}$ set of measurements, performed for each frequency.

Each set of measurements is a two-port measurement, obtaining m scattering matrices, $\mathbf{S}_{i-j}$, where i and j are the port number.

For a four-port (n =4), m =6 sets of measurements must be performed, for each frequency into the analysis frequency bandwidth. Each set of measurements is a two-port measurement, as it is shown in Fig. 1, obtaining the following 6 scattering matrices $\mathbf{S}_{i-j}$: $\mathbf{S}_{1-2}$, $\mathbf{S}_{1-3}$, $\mathbf{S}_{1-4}$, $\mathbf{S}_{2-3}$, $\mathbf{S}_{2-4}$ and $\mathbf{S}_{3-4}$.

The scattering matrices $\mathbf{S}_{i-j}$ must be re-normalized to the impedance corresponding to the loads connecting to the each port (the ports are open-ended in this method), obtaining m scattering parameter matrices, $\mathbf{S}'_{i-j}$, accordingly to the formula:

$$\mathbf{S}'_{i-j} = (\mathbf{I}_2 - \mathbf{\Gamma}_{i-j})^{-1} \cdot (\mathbf{S}_{i-j} - \mathbf{\Gamma}_{i-j}) \cdot (\mathbf{I}_2 - \mathbf{\Gamma}_{i-j} \cdot \mathbf{S}_{i-j})^{-1} \cdot (\mathbf{I}_2 - \mathbf{\Gamma}_{i-j}), \qquad (1)$$

where

$$\mathbf{\Gamma}_{i-j} = \begin{bmatrix} \Gamma_i & 0 \\ 0 & \Gamma_j \end{bmatrix},$$

and Γ_i, Γ_j are the reflection coefficients to the ports i and j, computed for the case when these ports are open-ended (the reference impedance being 50 Ω), while $\mathbf{I}_2$ is the unity matrix of order two.

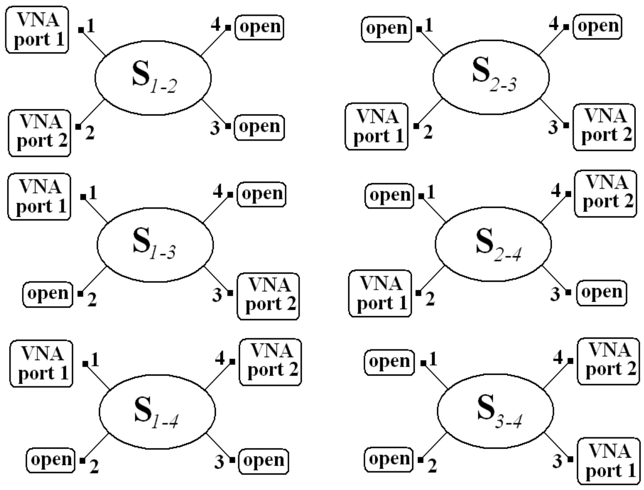


Fig. 1. The possible 6 combinations of two-port measurements (using a two-port VNA), for a four-port circuit.

For each open-ended port, the load impedances, or the reflection coefficients to the each port are not known before. Therefore, first of all, the reflection coefficients to the all $n = 4$ ports, $\Gamma_1, \ldots, \Gamma_4$ must be computed (theoretically these reflection coefficients are equal to 1, but these values must be known accurately). These reflection coefficients may be computed, minimizing the following functions:

$$\begin{aligned} S'_{1-2}[1,1] &= S'_{1-3}[1,1], \\ S'_{1-2}[1,1] &= S'_{1-4}[1,1], \\ S'_{1-2}[2,2] &= S'_{2-3}[1,1], \\ S'_{1-2}[2,2] &= S'_{2-4}[1,1], \end{aligned} \qquad (2)$$

where $S'_{i-j}[1,1]$ is the element of the $\mathbf{S}'_{i-j}$ matrix from the first row and the first column, while $S'_{i-j}[2,2]$ is the element of the $\mathbf{S}'_{i-j}$ matrix from the second row and the second column.

It may be shown that imposing (2), the conditions: $S'_{1-4}[2,2] = S'_{3-4}[2,2]$, $S'_{2-4}[2,2] = S'_{3-4}[2,2]$, $S'_{3-4}[1,1] = S'_{2-3}[2,2]$ and $S'_{3-4}[1,1] = S'_{1-3}[2,2]$ are also fulfilled.

In (2), the following analytical expression for $S'_{i-j}[1,1]$ and $S'_{i-j}[2,2]$ have been used (which were developed from (1)):

$$S'_{i-j}[1,1] = \frac{A}{B} \quad \text{and} \quad S'_{i-j}[2,2] = \frac{C}{B}, \tag{3}$$

where:

$$A = (S_{i-j}[1,1] - \Gamma_i) \cdot (1 - S_{i-j}[2,2] \cdot \Gamma_j) + S_{i-j}[1,2] \cdot S_{i-j}[2,1] \cdot \Gamma_j,$$

$$C = (S_{i-j}[2,2] - \Gamma_j) \cdot (1 - S_{i-j}[1,1] \cdot \Gamma_i) + S_{i-j}[1,2] \cdot S_{i-j}[2,1] \cdot \Gamma_i,$$

and

$$B = (1 - S_{i-j}[1,1] \cdot \Gamma_i) \cdot (1 - S_{i-j}[2,2] \cdot \Gamma_j) - S_{i-j}[1,2] \cdot S_{i-j}[2,1] \cdot \Gamma_i \cdot \Gamma_j.$$

Using (3) in (2) the reflection coefficients, $\Gamma_1, \ldots, \Gamma_4$, may be obtained.

Therefore, the all n=4 matrices $\mathbf{S}'_{i-j}$ have been obtained numerically with (1), so, the matrix for the 4-port circuit having the all ports open-ended may be constructed as follows:

$$\mathbf{S}' = \begin{bmatrix} S'_{1-2}[1,1] & S'_{1-2}[1,2] & S'_{1-3}[1,2] & S'_{1-4}[1,2] \\ S'_{1-2}[2,1] & S'_{1-2}[2,2] & S'_{2-3}[1,2] & S'_{2-4}[1,2] \\ S'_{1-3}[2,1] & S'_{2-3}[2,1] & S'_{1-3}[2,2] & S'_{3-4}[1,2] \\ S'_{1-4}[2,1] & S'_{2-4}[2,1] & S'_{3-4}[2,1] & S'_{1-4}[2,2] \end{bmatrix}. \tag{4}$$

Finally, the scattering matrix of the circuit (given by (4)) is re-normalized from the load impedances corresponding to the open ports, to 50 Ω, using the formula:

$$\mathbf{S} = (\mathbf{I}_4 - \boldsymbol{\Gamma})^{-1} \cdot (\mathbf{S}' - \boldsymbol{\Gamma}) \cdot (\mathbf{I}_4 - \boldsymbol{\Gamma}\mathbf{S}')^{-1} \cdot (\mathbf{I}_4 - \boldsymbol{\Gamma}),$$

where $\mathbf{I}_4$ is the unity matrix of order 4 and

$$\boldsymbol{\Gamma} = \begin{bmatrix} -\Gamma_1 & 0 & 0 & 0 \\ 0 & -\Gamma_2 & 0 & 0 \\ 0 & 0 & -\Gamma_3 & 0 \\ 0 & 0 & 0 & -\Gamma_4 \end{bmatrix}.$$

3. Description of the test circuit used for the method validation

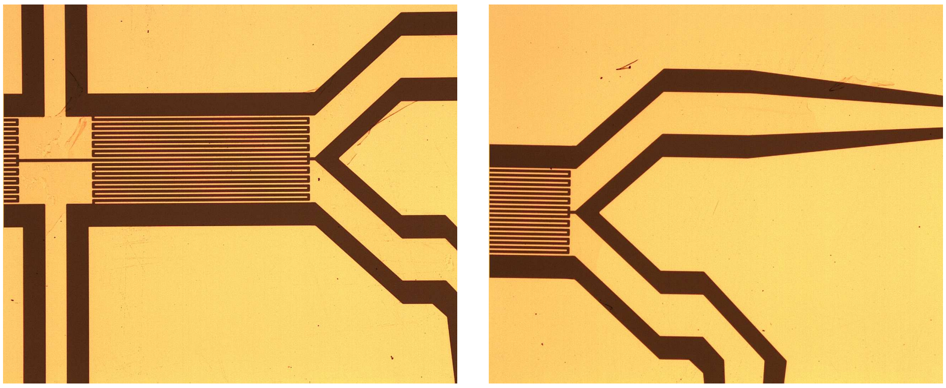
For the validation of the experimental method proposed in the previous section, a 4-port circuit, in particular a coupler [7], has been experimentally characterized. A short description of the coupler, including the technological fabrication is given below.

The coupler is a two coupled CRLH TLs, each one consisting of two identical cascaded cells of series connected capacitors and parallel connected CPW (CoPlanar Waveguide) open stubs [7]. The CRLH cells were designed such as to obtain a balanced structure for the coupler central frequency (equal to 11 GHz). This means that the series and parallel resonance frequencies must be equal and equal to the central frequency of the coupler [8].

Technological manufacturing of the coupler consists of one mask standard positive photolithography process. The substrate used was silicon of high resistivity covered by thermal SiO_2 of 1 μm thickness. On this substrate, 500 Å Cr layer followed by 0.6 μm Au has been evaporated on the entire surface. Using the glass mask, the metallization pattern has been defined by wet etching. The microscope photo of the circuit is shown in Fig. 2. At the all four ports of the directional coupler, tapered CPW lines have been used for the impedance matching to 50 Ω, as well as to fit the ports size to the on-wafer probe heads of the measurement system. The electrical lengths for the all these CPW lines are equal.

4. Experimental and numerical results

For the measurements performed on the coupler described in the previous section, a network analyzer (HP 8510C) and on-wafer probe heads station (Karl Süss PM5) have been used. Accordingly to the coupler layout, the port no. 1 is the input port, the port no. 2 is the coupled port, the port no. 3 is the through port and the port no. 4 is the isolated port.



(a) (b)

Fig. 2. Microscope photos of the fabricated coupler. Details for the interdigital capacitors and the CPW stubs area (a) and for the tapered CPWs area (b).

Following the method presented in Section 2, they were obtained the magnitudes of the experimental scattering parameters S_{11}, S_{21}, S_{31} and S_{41} shown in Fig. 3. The simulated magnitudes of the scattering parameters S_{11}, S_{21}, S_{31} and S_{41} for the coupler have been obtained by using IE3D-Zeland [9] and the results are presented in Fig. 4. Figure 5 shows the simulated and the experimental results for the phase difference between the coupled port and the through port.

By analyzing Figs. 3 and 4, for the frequency bandwidth of 10–12 GHz, the experimental coupling is 5 dB ± 1dB, being in good agreement with the simulated results. The experimental input return-loss and isolation are better than 20 dB for the same frequency bandwidth, a good agreement between simulated and experimental results being also observed. Also, from Fig. 5, the experimental phase difference between the coupled port and the through port is 80–100 degs. for frequencies between 10.25–11.5 GHz, the simulated results being closed to them.

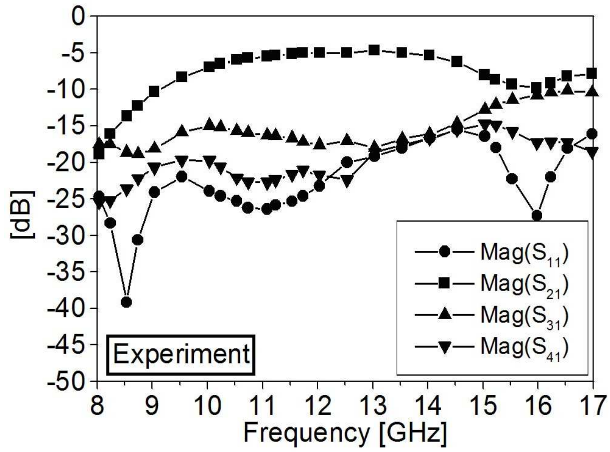


Fig. 3. Experimental scattering parameters, for the 4-port test circuit (a coupler).

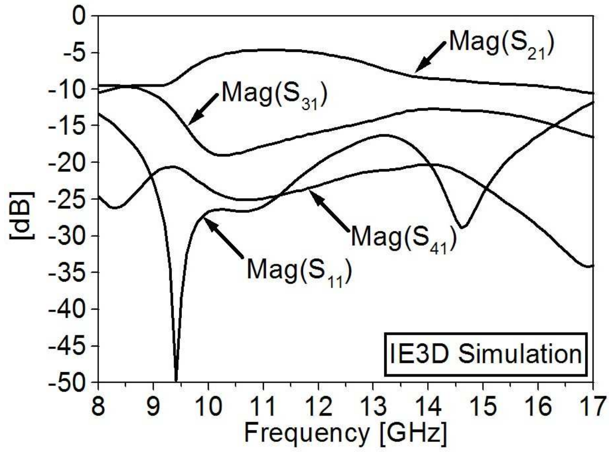


Fig. 4. Simulated scattering parameters, for the 4-port test circuit (a coupler).

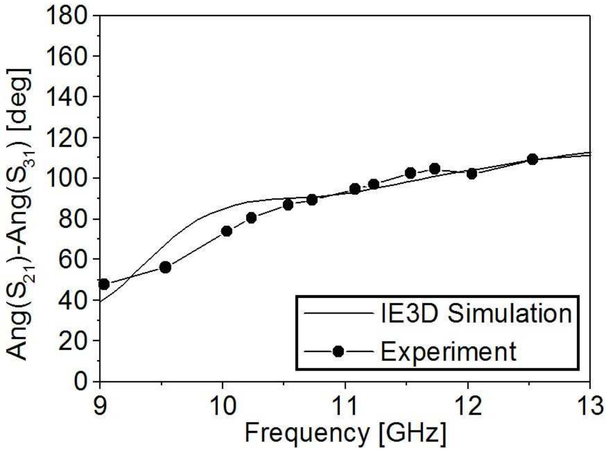


Fig. 5. Simulated and experimental phase difference between the coupled port and the through port of the coupler considered as a test 4-port circuit.

5. Conclusions

An experimental technique to characterize a 4-port circuit using a two-port VNA, has been proposed. For this method, 6 sets of two-port measurements must be performed, while the other two ports may be let open. The method is applied for a coupler, showing a good agreement between the experimental results and the expected ones obtained by simulation. For a number of ports greater than 4, the difficulties of applying this method is expected to grow substantially.

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