ON-WAFER EXPERIMENTAL CHARACTERIZATION FOR A 4-PORT CIRCUIT, USING A TWO-PORT VECTOR NETWORK ANALYZER

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Abstract–*The paper presents an experimental method useful to characterize 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.*

Keywords: *Vector network analyzer, on-wafer measurement, scattering matrices*

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 micro-wave multi-port circuits could be made by using a two-port VNA based connectors, by matching the other $n-2$ ports to 50Ω, 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 50Ω 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]), but here the load impedances connected to the ports (different from 50Ω) must be known.

The proposed method is applied for a coupler (designed in [7]), 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:

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

where

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

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 50Ω), while $\mathbf{I}_2$ is the unity matrix of order two.

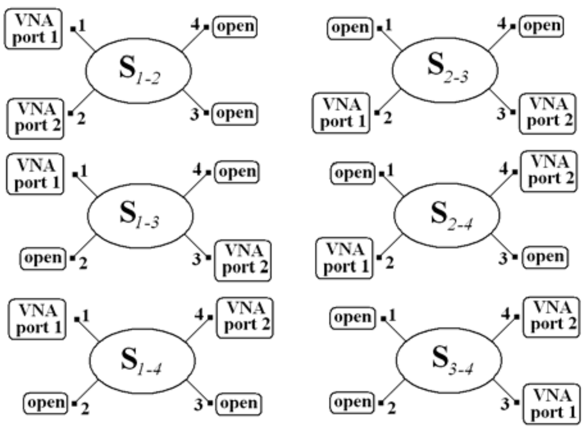

Fig. 1. The possible two-port measurements (using a two-port VNA), for a four-port circuit.

Because each port is open, then, 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 more accurately). These reflection coefficients may be computed, minimizing the following functions:

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

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:

$$S'_{1-4}[2,2] = S'_{3-4}[2,2],\ S'_{2-4}[2,2] = S'_{3-4}[2,2],$$
$$S'_{3-4}[1,1] = S'_{2-3}[2,2],\ S'_{3-4}[1,1] = S'_{1-3}[2,2]$$

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)):

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

and

$$S'_{i-j}[2,2] = \frac{C}{B} \tag{3b}$$

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:

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

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

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

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

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

3. EXPERIMENTAL AND NUMERICAL RESULTS

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, following the algorithm presented in the previous section.

For the measurements performed on the circuit, a network analyzer (HP 8510C) and on-wafer probe heads station (Karl Süss PM5) have been used.

These results are presented in Fig. 2, for the magnitude of the scattering parameters S_{11}, S_{21}, S_{31} and S_{41}.

The simulated magnitudes of the scattering parameters S_{11}, S_{21}, S_{31} and S_{41} for the test circuit are shown in Fig. 3.

Fig. 4 shows the simulated and the experimental results for the phase difference between the coupled port and the through port.

By analyzing Figs. 2 and 3, 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

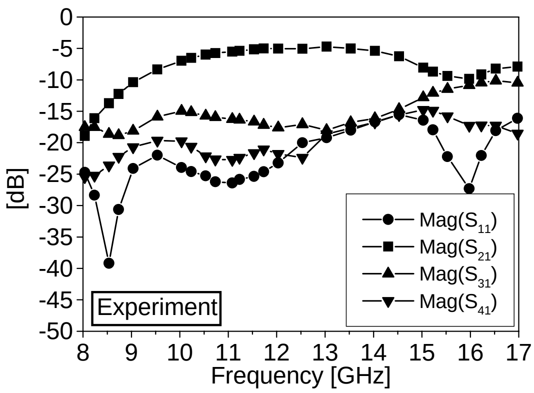

Fig. 2. Experimental scattering parameters, for the 4-port test circuit (a coupler).

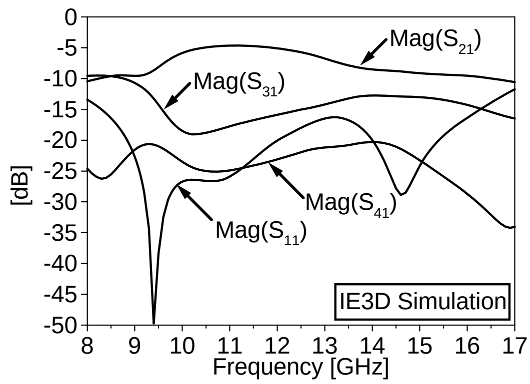

Fig. 3. Simulated scattering parameters, for the 4-port test circuit (a coupler).

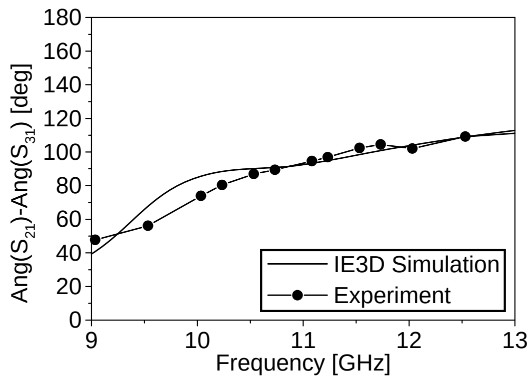

Fig. 4. Simulated and experimental phase difference between the coupled port and the through port of the coupler considered as a test 4-port circuit.

better than 20dB for the same frequency bandwidth, a good agreement between simulated and experimental results being also observed. From Fig. 4, the experimental phase is 80–100 deg. for frequencies between 10.25–11.5 GHz, the simulated results being closed to them.

4. CONCLUSIONS

An experimental technique to characterize a 4-port using a two-port VNA, has been proposed. For this method 6 sets of two-port measurements must be performed, while the other ports may be let open. The method is applied for a 4-port test circuit (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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