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Measurement of Multi-Port *S*-Parameters using Four-Port Network Analyzer

Jongmin Kim, Duc Long Luong, Wansoo Nah, and SoYoung Kim

***Abstract*—An efficient measurement methodology is proposed to construct the scattering parameters of a multi-port device using a four-port vector network analyzer (VNA) without the external un-terminated ports. By using the four-port VNA, the reflected waves from the un-terminated ports could be minimized. The proposed method significantly enhances the accuracy of the *S*-parameters with less number of measurements compared to the results of classical renormalization technique which uses two-port VNA. The proposed method is validated from the measured data with the coupled 8-port micro-strip lines.**

***Index Terms*—Scattering parameter measurement, multi-port device, renormalization, four-port VNA**

I. INTRODUCTION

Measuring multi-port scattering parameters (*S*-parameters) using a two-port vector network analyzer (VNA) has been widely used because it can be done at low cost with simple calibration. However, to obtain accurate *N*-port measurement with two-port VNA, certain conditions need to be met at the external terminations [1-6]. I. Rolfes found that one needs to know at least one external termination except the ports where the VNA is connected [3], and D.G. Kam showed that probing pads having almost unity reflection coefficients can enable the use of the two-port renormalization technique to characterize an eight-port device [4]. C.-J. Chen performed error and accuracy analyses for scattering parameter renormalization techniques using a two-port VNA [5].

In this letter, an efficient method to re-construct the multi-port *S*-parameters without knowing the exact reflection coefficients at the external terminations by employing a four-port VNA is proposed. Compared to the traditional method of using the two-port measurement, the measurement and data processing time can significantly be minimized. The *S*-parameters derived from proposed renormalized *S*-parameters matches the true *S*-parameters from the matched terminations, while the conventional two-port renormalization method showed a notable discrepancy without the exact knowledge of the reflection coefficients. Eight-port micro-strip lines were fabricated and tested to verify the validity of the proposed method.

II. PROPOSED METHOD

The scattering matrix renormalization formula is expressed as

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

where S is the N-port scattering matrix that is being normalized with port-referenced-impedance ζ_i, S' is the transformed scattering matrix when the port impedances are altered to Z_i, Γ is the diagonal matrix of reflection coefficients of Z_i seen from line impedances ζ_i, and I is the $N \times N$ identity matrix [1].

The flow of the proposed four-port renormalization

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Department of Semiconductor Systems Engineering, College of Information and Communication Engineering, Sungkyunkwan University, Suwon, Korea
E-mail : ksyoung@skku.edu

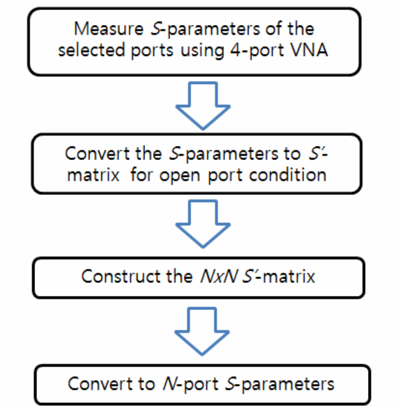

Fig. 1. Proposed four-port method.

technique is shown in Fig. 1. First, the ports that are connected to the 4-port VNA are selected. The four ports need to be the two pair of ports belonging to the same net. While the *N*-port reconstruction method based on two-port measurement requires the number of ${}_{N}C_{2}$ measurements, 4-port measurement requires the number of ${}_{N/2}C_{2}$ measurements. As a result, the efficiency of the proposed method is higher as the number of ports becomes larger. Furthermore, by connecting the four ports of DUT to 4-port VNA appropriately, the reflected waves can be minimized without knowing the external port terminations. The measured 4-port *S*-parameters are converted to *S'*-matrix with the open port condition using (1), and then the $N \times N$ *S'*-matrix is constructed from the multiple sub-matrices. The construction of *S'*-matrix is explained in the next section using a test case. Then the whole *S'*-matrix is re-normalized to obtain the final *S*-parameters as described in [1].

III. Model Validation

In order to verify the algorithm, the measurement was carried out with eight-port coupled micro-strip lines shown in Fig. 2. Each trace on the FR4 substrate had a width of 0.5 mm, and the traces were spaced apart 1.9 mm from each other.

Table 1 shows the ports connected to the four-port VNA at each measurement. It is an eight port test structure so the number measurement that needs to be taken for reconstruction is 6, while two-port requires 28 measurements.

The measurement can be performed on (1,2,3,4), (1,2,5,6), but not on (1,3,5,6), (2,4,6,8) assuming that the inside routing information is known. At each measurement, the four ports of the device under test (DUT) are connected to the VNA, and the remaining four ports are kept open. The construction of *8×8* *S'*-matrix from *4×4* matrices from measurements of Table 1 is shown in Fig. 3. By including the *4×4* matrix of M1, M4, and M6, the reflection coefficients of all the ports are included in the main diagonal. For M2, M3, and M5, only the off-diagonal elements need to be included. The final *S*-parameters can be calculated from *S'*-matrix using (1). To obtain the true *S*-parameters of this circuit as a reference, broadband 50 Ω was used for the external terminations of the other four ports which are not connected to VNA.

The measured and the renormalized *S*-parameters are

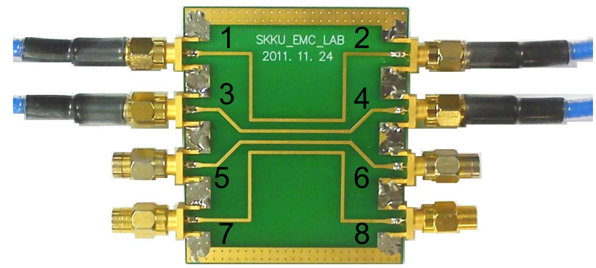

Fig. 2. Eight-port coupled micro-strip lines.

Table 1. Port connectivity of the proposed 4-port measurement scheme

No.	Ports connected to four-port VNA
1 (M1)	1,2,3,4
2 (M2)	1,2,5,6
3 (M3)	1,2,7,8
4 (M4)	3,4,5,6
5 (M5)	3,4,7,8
6 (M6)	5,6,7,8

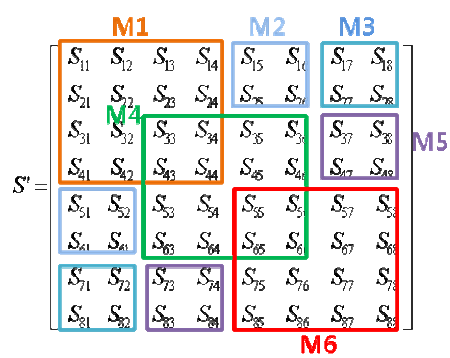

Fig. 3. *S'*-matrix construction from 4-port VNA measurement.

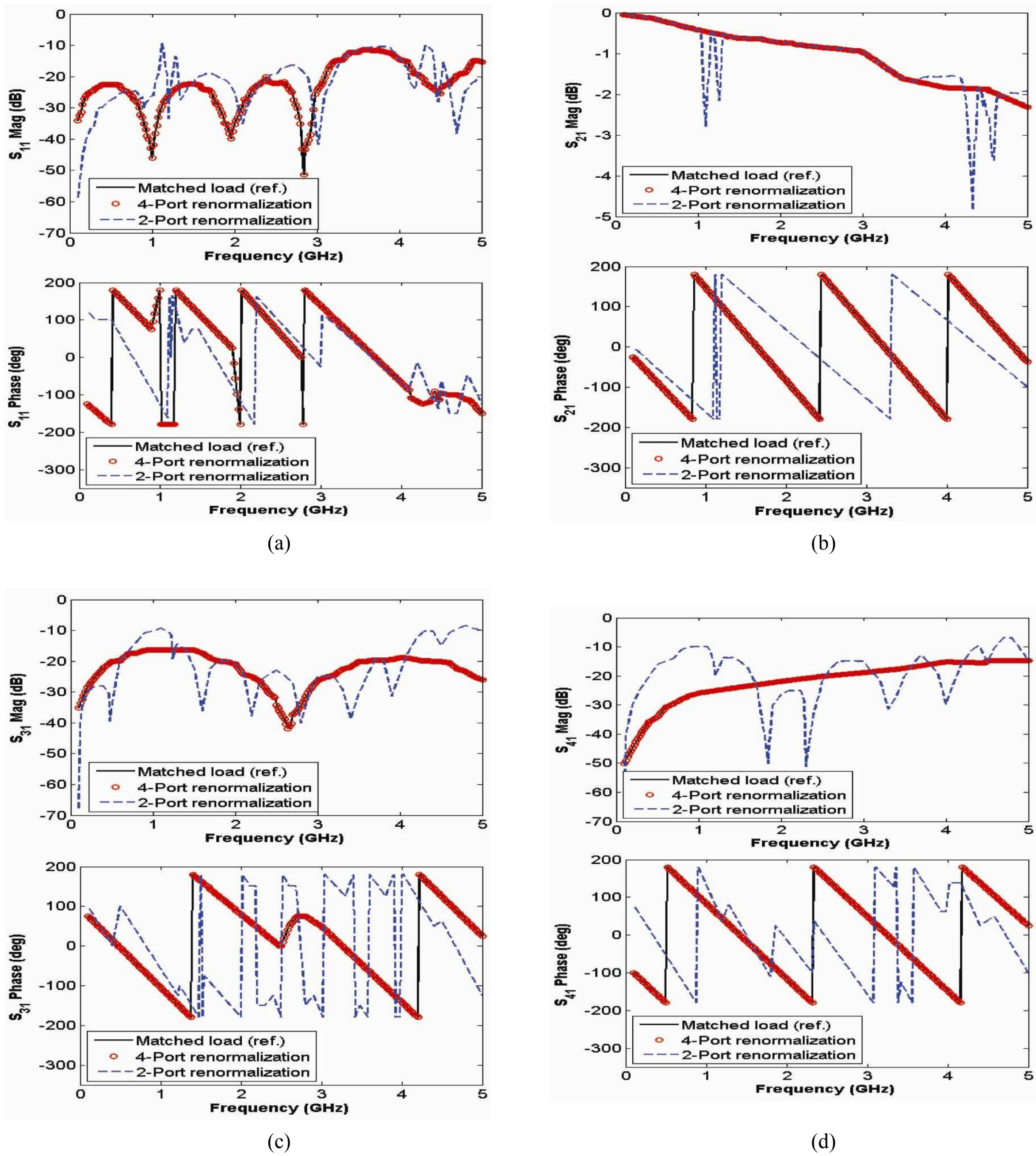

Fig. 4. Measured and renormalized S-parameters (a) S_{11}, (b) S_{21}, (c) S_{31}, (d) S_{41}.

shown in Fig. 4, and the accuracy of the four *S*-parameters out of 64 is shown because of the space limit. It is clear that the *S*-parameters from the proposed 4-port renormalization method coincide almost exactly to the true *S*-parameters in both magnitude and phase. The data from classical 2-port renormalization scheme, however, show large discrepancy in both magnitude and phase. This is because the conventional two-port renormalization scheme cannot avert the reflected waves coming into the VNA port because it has only two ports to use, meanwhile the proposed four-port renormalization scheme has some freedom to take other ports, minimizing the reflected waves coming into the VNA. In the calculation process for the renormalization, we used 1MΩ for the external terminations for both two-port and four-port methods. It is good to notice that the *S*-parameters from the proposed four-port renormalization coincide very well to the true *S*-parameters even though the 1MΩ we used was just a rough estimate of the external terminations.

The accuracy of the proposed method can degrade when the coupling factor of the micro-strip lines becomes very high due to the reflected waves from the coupled lines which are terminated unmatched. Nevertheless, from the practical measurement point of view, the enhancement in the measurement is useful especially when the matched termination is impossible due to structural reasons.

IV. CONCLUSIONS

A novel multi-port *S*-parameter measurement with four-port VNA is presented. In selecting the ports to be measured, the routing information in DUT is necessary. Compared to the traditional multi-port measurement method based on two-port VNA, the number of measurements is significantly reduced and the information on reflection coefficients for the external un-terminated ports is not necessary. By properly selecting the VNA ports, a significant amount of reflection was reduced, and the *S*-parameters were renormalized as if they were terminated with matched loads, while the classical two-port renormalized method showed notable discrepancies. The proposed method is validated through the eight-port coupled micro-strip lines, and it seems that this measurement method will be useful in crosstalk analysis of connector circuit where the routing information is usually clear.

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Jongmin Kim received B.S. degree in Information Communication Engineering from Dongeui University, Busan, Korea in 2006 and M.S degrees in Electronics Engineering from Sungkyukwan University in Korea and he is currently a Ph.D candidate in the department of electrical and electronics engineering at Sungkyunkwan University. His research interests Signal/Power Integrity and Co-simulation in the time domain to increase reliability in high-speed digital system.

Duc Long Luong received Bachelor's degree in Electronics and Telecommunications from Hanoi University of Technology, Vietnam in 2010, and the Master's degree in electrical engineering from Sungkyunkwan University, Korea in 2012. He is now working as a microwave engineer at the Viettel Institute of Research and Development, Viettel Group, Vietnam since December, 2012.

Wansoo Nah received B.S., M.S. and Ph.D. degree from Electrical Engineering Department, Seoul National University, Korea, in 1984, 1986 and 1991 respectively. He has been with Sungkyunkwan University in Korea since 1995, and now is a professor at the College of Information and Communication Engineering. He was a guest researcher at SSCL (Super-conducting Super Collider Laboratory) in USA from 1991 to 1993, and was also with KERI (Korea Electrical Research Institute) in Chang-won, Korea as a senior researcher from 1991 to 1995. His primary interests are analysis/development of SI (signal integrity), PI (power integrity) on board and chip level, and EMI (Electromagnetic Interference) reduction techniques.

SoYoung Kim received a B.S. degree in Electrical Engineering from Seoul National University, Seoul, Korea in 1997 and M.S. and Ph.D. degrees in Electrical Engineering from Stanford University, Stanford, CA in 1999 and 2004, respectively. From 2004 to 2008, she was with Intel Corporation, Santa Clara, CA, where she worked on parasitic extraction and simulation of on-chip interconnects. From 2008 to 2009, she was with Cadence Design Systems, San Jose, CA, where she worked on developing IC power analysis tools. She is currently an Associate Professor with the Department of Semiconductor Systems Engineering, College of Information and Communication Engineering, Sungkyunkwan University, Suwon, Korea. Her research interests include device and interconnect modeling, signal integrity, power integrity and electromagnetic interference in electronic systems.