An improved method for TRL calibration

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***Abstract*— Based on the ten-term error model of a two-port vector network analyzer (VNA) measurement system, the TRL (Thru-Reflect-Line) calibration is implemented. Then ten error terms of fixtures are derived directly from the S parameters of the calibration kits measured from the coaxial reference plane without converting S parameters to T parameters. To test our algorithm, two test boards with different via diameters are designed and measured. By comparing with Engen's TRL algorithm it is certified that those equations are available over a wide frequency range.**

I. INTRODUCTION

A major problem encountered when using vector network analyzer to obtain the scatter parameters of a non-coaxial DUT (Device Under Test) such as microstrip or coplanar waveguide is the need to separate the errors of the fixtures[1]. Because of the non-coaxial DUTs, two or more fixtures are needed to connect the non-coaxial DUTs and the coaxial test ports of VNA. The S parameters of those fixtures are consequently introduced into the measurement results as errors. To get the S parameters of DUTs, the effect of the fixtures should be removed.

The TRL (Thru-Reflect-Line) calibration, a full two-port calibration method using three standards: THRU, REFLECT and LINE, is often employed [1][2]. It was first presented by Engen in 1979[2]. In Engen's algorithm, transfer scattering parameter (T parameter) was used to obtain the error terms of the fixtures. In recent years, this method has been proved useful on on-wafer devices[3], microwave circuits[4], etc.

In this paper, ten error terms of fixtures are considered in order to model the measurement system. Then using TRL calibration method, the ten error terms are solved directly from the measurement results without converting them to T parameters at the first beginning of the calibration. The problem of root choice[2][5] is also encountered in our algorithm. A simple but useful strategy is applied to select the right roots. To test our algorithm, two test boards are measured with TRL calibration. The results agree well with Engen's algorithm.

II. MODELING

In a VNA measurement sysmtem the fixtures and DUT can be regarded as two-port networks. A signal flow diagram in Fig. 1 describes how the signals transfer in a measurement system. The S parameters subscripted by 'A' and 'B' denote the networks of fixture A and fixture B respectively. And the S parameters subscripted by 'M' denote the parameters measured from the coaxial reference plane by vector network analyzer and those with 'X' are the S parameters of DUT. C_F and C_R denote the forward leakage error and reverse leakage error respectively.

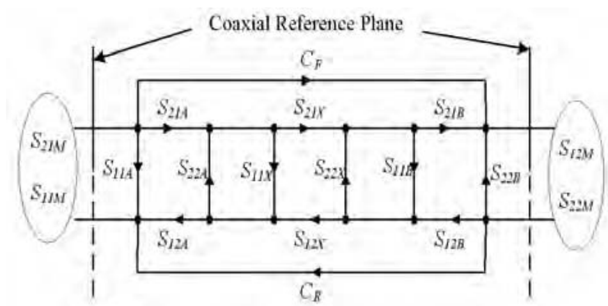

Fig. 1. Two-port 10-term errors model.

There are three steps to implement TRL calibration by connecting THRU ($S_{11} = S_{22} = 0$, $S_{12} = S_{21} = 1$), REFLECT ($S_{11} = S_{22} = \Gamma$) and LINE ($S_{11} = S_{22} = 0$, $S_{12} = S_{21} = X$) standards to the fixtures respectively. Both Γ and X are unknown but can be solved. Three measurements are implemented then and three sets of S parameters are obtained from the coaxial reference plane. Each set contains four S parameters: S_{11}, S_{21}, S_{12}, and S_{22}. Let superscripts 'T', 'R' and 'L' denote the S parameters of the calibration kits, THRU, REFLECT and LINE, which are obtained from the coaxial reference plane respectively. Then the error terms can be solved as follows.

$$C_F = S_{21M}^S, \qquad C_R = S_{12M}^S \tag{1}$$

$$S_{22A} = \frac{W}{\Gamma(1+W)}, \qquad S_{11B} = \frac{V}{\Gamma(1+V)} \tag{2}$$

$$S_{11A} = S_{11M}^T - \frac{(1-AX^2)(S_{11M}^T - S_{11M}^L)}{1-X^2} \tag{3}$$

$$S_{22B} = S_{22M}^T - \frac{(1-AX^2)(S_{22M}^T - S_{22M}^L)}{1-X^2} \tag{4}$$

$$T = S_{21A}S_{21B} = (S_{21M}^T - S_{21M}^S)(1-A) \tag{5}$$

$$P = S_{12A}S_{12B} = (S_{12M}^T - S_{12M}^S)(1-A) \tag{6}$$

$$Z = S_{21A}S_{12A} = \frac{S_{11M}^T - S_{11M}^L}{S_{11B}(\frac{1}{1-A} - \frac{X^2}{1-AX^2})} \tag{7}$$

$$Y = S_{21B}S_{12B} = \frac{S_{22M}^T - S_{22M}^L}{S_{22A}(\frac{1}{1-A} - \frac{X^2}{1-AX^2})} \tag{8}$$

where

$$X = \frac{-b \pm \sqrt{b^2 - 4(S_{21M}^S - S_{21M}^T)(S_{12M}^L - S_{12M}^S)(S_{21M}^L - S_{21M}^S)(S_{12M}^S - S_{12M}^T)}}{2(S_{21M}^S - S_{21M}^T)(S_{12M}^L - S_{12M}^S)} \tag{9}$$

$$b = (S_{21M}^S - S_{21M}^T)(S_{12M}^S - S_{12M}^T) + (S_{12M}^L - S_{12M}^S)(S_{21M}^L - S_{21M}^S) + (S_{22M}^L - S_{22M}^T)(S_{11M}^T - S_{11M}^L) \tag{10}$$

$$A = \frac{S_{22M}^T - S_{22M}^L}{(S_{12M}^T - S_{12M}^S) - (S_{12M}^L - S_{12M}^S)X} \cdot \frac{S_{11M}^T - S_{11M}^L}{(S_{21M}^T - S_{21M}^S) - (S_{21M}^L - S_{21M}^S)X} \tag{11}$$

$$W = \frac{S_{22M}^T - S_{22M}^L}{(S_{12M}^T - S_{12M}^S) - (S_{12M}^L - S_{12M}^S)X} \cdot \frac{S_{11M}^S - S_{11M}^T}{(S_{21M}^T - S_{21M}^S)(1-A)} + \frac{A}{1-A} \tag{12}$$

$$V = \frac{S_{11M}^T - S_{11M}^L}{(S_{21M}^T - S_{21M}^S) - (S_{21M}^L - S_{21M}^S)X} \cdot \frac{S_{22M}^S - S_{22M}^T}{(S_{12M}^T - S_{12M}^S)(1-A)} + \frac{A}{1-A} \tag{13}$$

$$\Gamma = \pm\sqrt{\frac{WV}{(1+W)(1+V)A}} \tag{14}$$

Among the equations mentioned above, each of (9) and (14) contains two roots. For X, the strategy for root choice is as follows.

- The phase should be continuous except at $\pm 180°$ and keeps decreasing from $+180°$ to $-180°$ and then jumps to $+180°$ again and repeats. It changes versus the frequency.
- As to the magnitude, it must satisfy the restriction as $|X| \leq 1$.

For Γ, the magnitudes of the two roots of (14) are equal to each other, so the choice of proper root mainly depends on the phase. The restriction for root choice is to make sure the phase is continuous except at $\pm 180°$.

III. Simulation and Results

To examine (1) $\sim$ (14), two test boards with via holes of different size are measured with TRL calibration from $10MHz$ to $20GHz$. The results calibrated by (1) $\sim$ (14) are compared with those calibrated using Engen's algorithm.

The structure of the test boards and the photograph are shown in Fig.2 and Fig.3 respectively. The substrate material of the test boards is NH9320 with the permittivity $3.2 - 0.008i$. The diameter of one via hole is $0.35mm$ and that of the other is $0.7mm$. The S parameters of the test boards calibrated using different TRL calibration methods are shown in Fig.4 $\sim$ Fig.7.

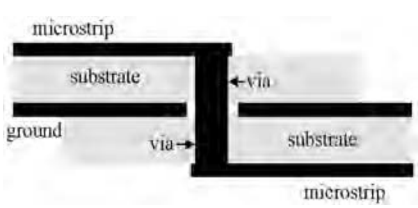

Fig. 2. Side view of a test board.

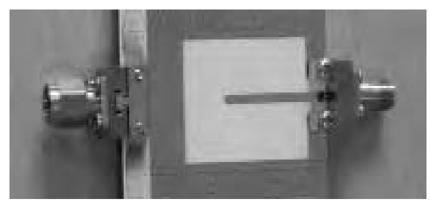

Fig. 3. Photograph of a test board.This test board is connected by two coaxial fixtures.

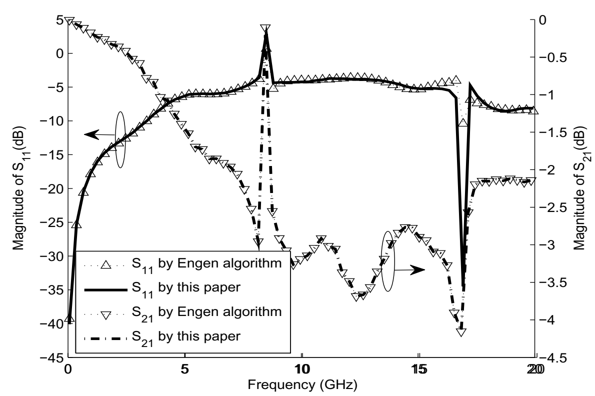

Fig. 4. The S parameters of the test board with a $0.35mm$ via hole.

IV. Conclusion

Compared with Engen's algorithm, the equations proposed in this paper are effective on non-coaxial test boards measurement procedure. Using the strategy of root choice , the values of Γ and X are selected correctly. The equations work well over a wide frequency range. They don't require the test fixtures to be reciprocal and are easy to be realized by programming.

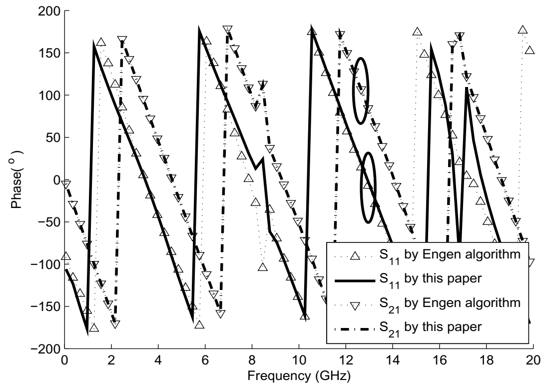

Fig. 5. The S parameters of the test board with a $0.35mm$ via hole.

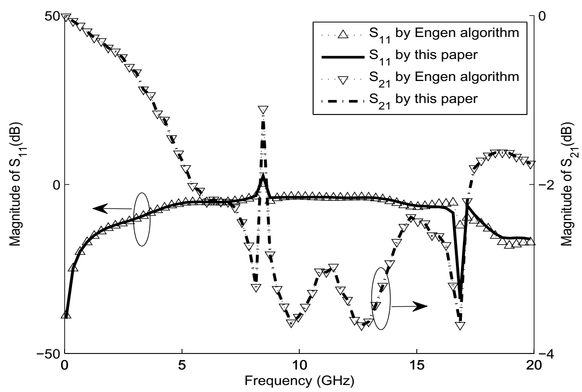

Fig. 6. The S parameters of the test board with a $0.7mm$ via hole.

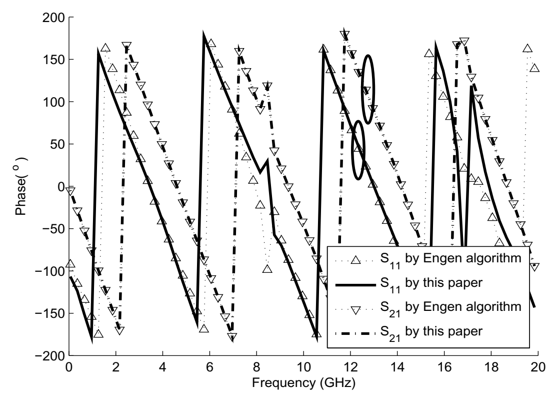

Fig. 7. The S parameters of the test board with a $0.7mm$ via hole.

V. Acknowledgment

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