Frequency Limitation in the Calibration of Microwave Test Fixtures

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***Abstract*—The problem of frequency limitation arising from the calibration of asymmetric and symmetric test fixtures has been investigated. For asymmetric test fixtures, a new algorithm based on the thru–short–match (TSM) method is outlined. It is found that the conventional TSM method does not have any inherent frequency limitation, but using the same procedure with an unknown match may lead to the said problem. This limitation can be avoided by using a different algorithm. The various calibration methods for symmetric test fixtures using known standards are also discussed and the origin of the frequency limitation is identified. Several ways in avoiding the problem are proposed. There is good agreement between the theories and experimental data.**

***Index Terms*—Calibration, deembedding, microwave network analyzer, scattering parameter measurement, test fixture.**

I. INTRODUCTION

THE S-parameters of test fixtures can be obtained from the measurements made at the reference planes of a calibrated microwave network analyzer using a set of known devices (standards) as test devices. This procedure is referred to as unterminating or calibrating the test fixtures [1]. In the past two decades, many calibration methods have been established [2]–[11]. The thru–short–delay (TSD) [2] and the thru–reflect–line (TRL) [3] methods use two transmission-line standards, and the calibration equations obtained using these two line standards are linearly dependent at the frequencies $nc/2(L_L - L_T)$, where n is an integer, c is the velocity of light, and L_L and L_T are the lengths of the line and thru, respectively. Thus, the calibration becomes very inaccurate at these periodic frequencies, and this is a typical example of an inherent frequency limitation. For the thru–short–open (TSO) method, the calibration equations obtained using short and open standards have correlations with the equations of the thru standard at some frequencies periodically [12], therefore, this method also has a corresponding frequency limitation [12], [13]. The origin of the frequency limitation for some calibration methods that use only one transmission standard and a short or an open standard has not been reported. The problem is often mentioned in the literature, but up to now, no thorough investigation has been carried out.

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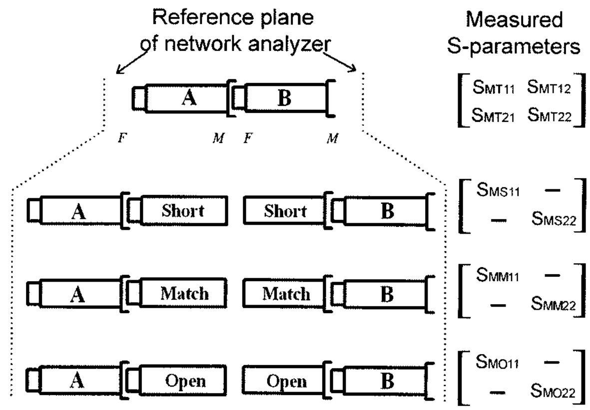

Fig. 1. Measurement configurations for the TSM and TOM methods. Networks A and B are test fixtures.

In this paper, an algorithm based on the thru–short–match (TSM) method is outlined for asymmetric test fixtures. The match standard is treated as an unknown in the calibration, and the suggested method can obtain higher accuracy than the conventional TSM method at the expense of frequency limitation, as given in Section II. Three methods using one known transmission-line standard and one known reflection standard for calibrating symmetrical test fixtures are discussed in Section III. It is found that, if the reflection coefficient of the standard approaches ± 1, the frequency limitation exists. Finally, discussions and conclusions are given in Section IV.

II. TSM AND THRU–OPEN–MATCH (TOM) METHODS

In most cases, test fixtures are reciprocal and asymmetrical/not identical. There are six S-parameters to be determined in the calibration of the asymmetrical test fixtures. Fig. 1 shows the measurement configuration for performing the TSM and TOM methods. An HP8720D network analyzer was calibrated using the short–open–load–thru (SOLT) calibration technique since this method is accurate and has no frequency limitation. The test ports 1 and 2 of the calibrated network analyzer were male and female, respectively. The calibration was carried out using the HP85052D coaxial calibration standards over the frequency range from 50 MHz to 20 GHz. The reference planes were located in such a way that the measured S-parameter S_{T21} for the thru standard equals $1 + j0$. In this study, the 6- and 3-dB coaxial attenuators were used as test fixtures A and B, respectively. The fixtures were reciprocal, asymmetrical, and could be measured using the calibrated network analyzer. Thus, a comparison can be made between our calculated results and the directly measured results.

In the following analysis, only the TSM method is considered. The relations among the S-parameters of the test fixtures and the standards can be described by the following equations [2], [7], [14]:

$$S_{A11} + kS_{B11}S_{T21}S_{MT12} = S_{MT11} \tag{1}$$

$$S_{A22}S_{MT11} - \Delta_A - \frac{kS_{MT12}}{S_{T12}} = 0 \tag{2}$$

$$kS_{B11}S_{MT22} - k\Delta_B - \frac{S_{MT21}}{S_{T21}} = 0 \tag{3}$$

$$S_{A22}S_{T12}S_{MT21} - kS_{MT22} + kS_{B22} = 0 \tag{4}$$

$$S_{A11} + S_{A22}S_{S11}S_{MS11} - \Delta_A S_{S11} = S_{MS11} \tag{5}$$

$$kS_{MS22} - kS_{B11}S_{S22}S_{MS22} - kS_{B22} + k\Delta_B S_{S22} = 0 \tag{6}$$

$$S_{A11} + S_{A22}S_{M11}S_{MM11} - \Delta_A S_{M11} = S_{MM11} \tag{7}$$

$$kS_{MM22} - kS_{B11}S_{M22}S_{MM22} - kS_{B22} + k\Delta_B S_{M22} = 0 \tag{8}$$

where

$$\Delta_X = S_{X11}S_{X22} - S_{X12}S_{X21}, \quad X = A \text{ and } B \tag{9}$$

$$k = \frac{S_{A21}}{S_{B12}} = \frac{S_{A11}S_{A22} - \Delta_A}{kS_{B11}S_{B22} - k\Delta_B}. \tag{10}$$

In the subscripts, the letters A and B stand for the test fixtures A and B, respectively, the first letter M stands for measured parameters if followed by another letter, and the letter after M indicates the standard inserted in between the fixtures. T, S, and M stand for the standards thru, short, and match, respectively. It has been shown that three among (1)–(4) are independent, and there are seven independent equations among (1)–(8). For the TSM and TOM methods, $S_{M11} = S_{M22} = 0$, and all the seven independent equations can be used to determine the following terms:

$$S_{A11} \quad S_{A22} \quad \Delta_A \quad k \quad kS_{B11} \quad kS_{B22} \quad k\Delta_B. \tag{11}$$

It has been shown that the TSM and TOM methods do not have the phase uncertainty problem and any frequency limitation [13]. However, their accuracies depend greatly on the precision of the standards used. Since there are only six S-parameters to be determined in the calibration of the test fixtures, one of the S-parameters of the standards can be regarded as an unknown, and can be determined using the redundant equation. A new algorithm based on the conventional TSM method has been proposed in our previous paper [14]. In this improved algorithm, the redundant calibration equation was used to determine the reflection coefficient of an imprecise short standard. Therefore, the effects of the imprecise short can be removed, and this improved method is more accurate than the conventional TSM method, with no phase uncertainty and no frequency limitation. In some test environments, the standard match can be less precise than the short. For example, a good short is much easier to obtain than a good match for a rectangular waveguide. In this case, the redundant equation can be used to determine the S-parameter of the match standard. In our analysis, the match standard is treated as an unknown, the terms required for the test fixture calibration are [14]

$$S_{A11} \quad S_{A22} \quad \Delta_A \quad kS_{B11} \quad S_{B22} \quad k\Delta_B. \tag{12}$$

These terms and the reflection coefficient of the match S_{M11} can be obtained by solving (2)–(8). Considering that $S_{S11} = S_{S22}$, $S_{M11} = S_{M22}$, and $S_{T12} = S_{T21} = 1$, and with the help of (10), we have (13)–(16), shown at the bottom of this page.

After S_{A11} is determined, all other terms listed in (12) can be obtained as follows:

$$kS_{B11} = \frac{S_{MT11} - S_{A11}}{S_{MT12}} \tag{17}$$

$$k\Delta_B = \frac{S_{MT22}(S_{MT11} - S_{A11}) - S_{MT12}^2}{S_{MT12}} \tag{18}$$

$$S_{A22} = \frac{(S_{A11} - S_{MS11})(S_{MS22} - S_{MT22}) + VS_{S11}^2}{R\,S_{T12}^2 S_{S11}} \tag{19}$$

with (20)–(23), shown at the bottom of the following page.

$$S_{A11} = \Big\{P(S_{MS11} - S_{MM11})(S_{MS22} - S_{MT22})S_{S11}^2\left[S_{MT12}^2 + S_{MT11}(S_{MS22} - S_{MT22})\right] - Q\,S_{MS11}(S_{MS22} - S_{MM22})S_{MT12}^2 \pm RS_{S11}S_{MT12}\sqrt{PQ(S_{MM11} - S_{MS11})(S_{MM22} - S_{MS22})}\Big\} \Big/ \left[(S_{MS11} - S_{MM11})(S_{MS22} - S_{MT22})^2 S_{S11}^2 + Q(S_{MM22} - S_{MS22})S_{MT12}^2\right] \tag{13}$$

where

$$P = S_{MT12}^2 - (S_{MS11} - S_{MT11})(S_{MM22} - S_{MT22}) \tag{14}$$

$$Q = S_{MT12}^2 - (S_{MM11} - S_{MT11})(S_{MS22} - S_{MT22}) \tag{15}$$

$$R = S_{MT12}^2 - (S_{MS11} - S_{MT11})(S_{MS22} - S_{MT22}) \tag{16}$$

Substituting (12)–(22) into (10) leads to

$$k = \frac{(S_{MT11} - S_{MS11})V\, S_{S11}^2 + (S_{MS11} - S_{A11})S_{MT12}^2}{R\, S_{MT12}S_{S11}}. \quad (24)$$

From (13), it can be seen that the solution has two roots. The allowed error in the choice of the correct root can be as large as ±90° [5]. The correct choice can be easily made by comparing the roots with the solution obtained using the conventional TSM method since the TSM method has a unique solution. In this case, the measured length of the thru is zero, and the measured offset length of the short L_s is approximately 9.54 mm. At frequencies $nc/4L_s = n \times 7.86\ GHz$, where n is an integer, c is the velocity of light in free space, $S_{S11} = \pm 1$, and these frequencies fulfill the following equation [12]:

$$R = S_{MT21}^2 - (S_{MS11} - S_{MT11})(S_{MS22} - S_{MT22}) = 0. \quad (25)$$

From (19), (21), and (24), it can be predicted that the denominators of these expressions approach zero at frequencies $n \times 7.86$ GHz. Fig. 2 shows the S-parameter S_{A11} obtained using the present method. The directly measured data are also plotted for comparison. Although it is hard to see that this method has a frequency limitation from (13), it is obvious that the accuracy of this method becomes very poor at frequencies $n \times 7.86$ GHz from Fig. 2. From the above analysis, one can see that when S_{A11} is determined, all terms required for test fixture calibration can be obtained. This means that this method does have a frequency limitation.

III. Thru–Short (TS) and Thru–Open (TO) Methods

In some cases, the test fixtures are almost identical. For example, the device under test is a two-port with microstrip input and output ports. The test fixtures can be two coax-to-microstrip transitions and can be identical or symmetrical. The required S-parameters of the symmetrical test fixtures reduce to S_{A11}, S_{A22}, and $S_{A12}S_{A21}$ [13]. In this case, two standards including one transmission standard are needed for calibrating symmetrical test fixtures. The methods using known standards are the thru–line (TL) [11], [15], the TS/TO [7], and the thru–match (TM) [10] methods. The TL method uses two transmission-line standards and has a frequency limitation.

In practical applications, exactly symmetric test fixtures are difficult to obtain. In the analysis, the triple-through method [4] is used to realize the hypothetical symmetrical fixture halves A and A'. The measurement configuration is shown in Fig. 3.

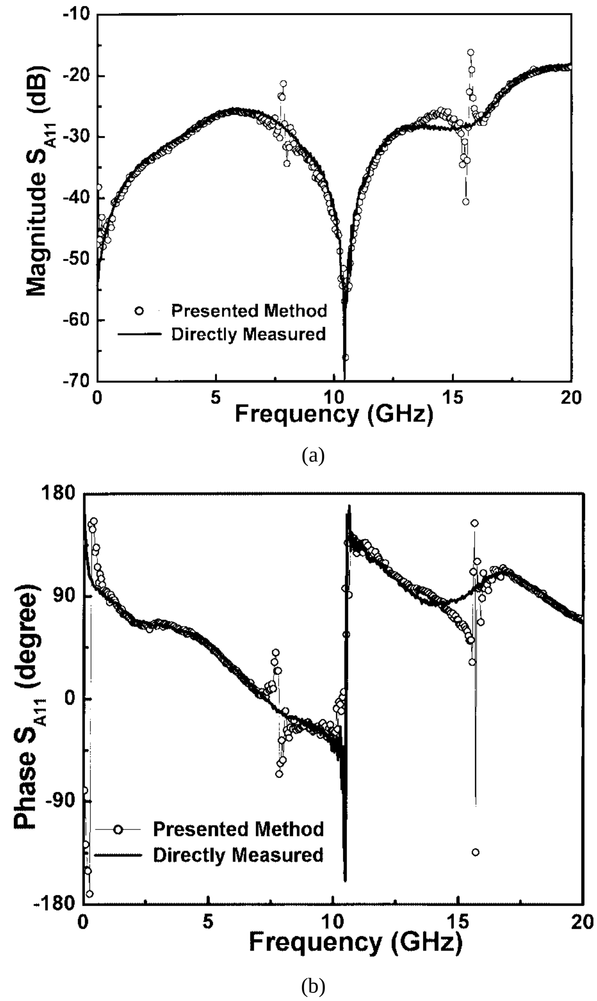

Fig. 2. Measured S-parameter S_{A11} using the new algorithm of the TSM method, compared with the data obtained using the full two-port SOLT method.

The fixtures considered in the analysis include two-ports A and B used in the above section and fixture C, which consists of two adapters of the HP85052 coaxial calibration kit with a 6-dB coaxial attenuator inserted in between. The adapters were used to convert the port sex of fixture C. The cascaded networks are indicated by the two letters, which stand for the two fixtures. For example, the measurable network AB is obtained by cascading two-ports A and B. Since the test ports 1 and 2 of the calibrated network analyzer are male and female, respectively, the subscripts 1 and 2 of the measured S-parameters of the cascaded networks AC and CB should be interchanged in order to

$$V = S_{MT12}^2 - (S_{A11} - S_{MT11})(S_{MS22} - S_{MT22}) \quad (20)$$

$$\Delta_A = \frac{(S_{A11} - S_{MS11})\left[S_{MT12}^2 + (S_{MS22} - S_{MT22})S_{MT11}\right] + V\, S_{MS11}S_{S11}^2}{R\, S_{S11}} \quad (21)$$

$$S_{B22} = \frac{(S_{A11} - S_{MS11})S_{MS22}S_{MT12}^2 + V\left[S_{MT12}^2 + (S_{MS11} - S_{MT11})S_{MT22}\right]S_{S11}^2}{(S_{A11} - S_{MS11})S_{MT12}^2 + (S_{MS11} - S_{MT11})VS_{S11}^2} \quad (22)$$

$$S_{M11} = \frac{S_{MM11} - S_{A11}}{S_{A22}S_{MM11} - \Delta_A} \quad (23)$$

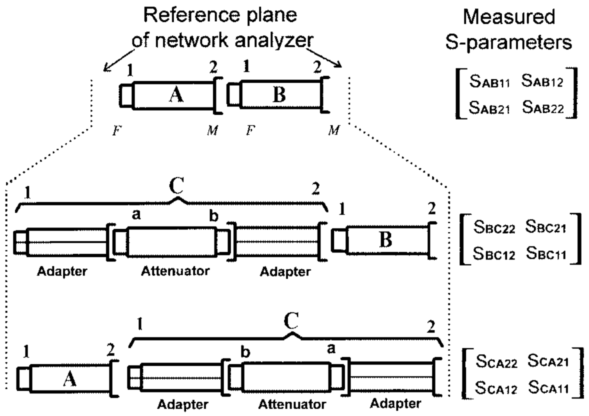

Fig. 3. Measurement configurations for the TS, TO, and TM methods; networks A and B are test fixtures.

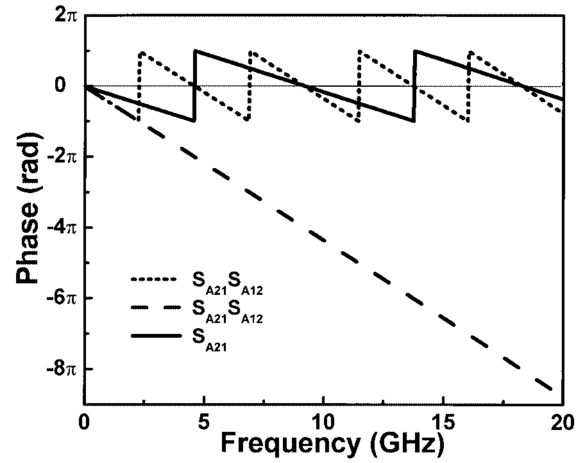

Fig. 4. Phase frequency responses of $S_{A21}S_{A12}$ and S_{A21}.

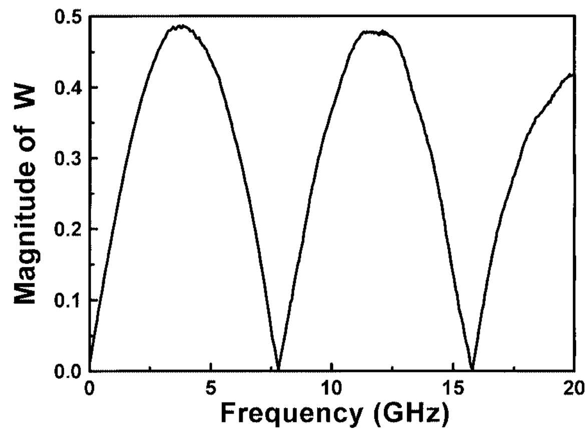

Fig. 5. Denominator of the S-parameter S_{A11} obtained using the TS method.

obtain the S-parameters of the required two-port networks CA and BC. All these changes are also shown in Fig. 3.

The transfer matrix of the thru connection of the hypothetical symmetrical fixture A–A' can be expressed as [4]

$$T_{AA} = T_{AB} I' T_{BC} I' T_{CA} \tag{26}$$

where

$$T_x = \frac{1}{S_{x21}} \begin{bmatrix} 1 & -S_{x22} \\ S_{x11} & -\Delta_x \end{bmatrix}$$

$$X = AB,\ BC,\ \text{or}\ CA \tag{27}$$

$$I' = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{28}$$

Going back to the S-parameters from transfer matrix T_{AA}, we have (29) and (30), shown at the bottom of this page.

Hence, the S-parameters of the cascaded symmetrical fixtures A and A' can be calculated from the measured S-matrices S_{AB}, S_{BC}, and S_{CA}. On the other hand, if the two real symmetrical fixtures A and A' are cascaded together, the transfer matrix of this cascaded network can be given by [4]

$$T_{AA} = T_A I' T_A^{-1} I' \tag{31}$$

and its S-parameters can be expressed as

$$S_{AA11} = S_{AA22} = \frac{S_{A11} - S_{A22}\Delta_A}{1 - S_{A22}^2} \tag{32}$$

$$S_{AA21} = S_{AA12} = \frac{S_{A12}S_{A21}}{1 - S_{A22}^2}. \tag{33}$$

Rewriting these equations leads to

$$S_{A22} = \frac{S_{AA11} - S_{A11}}{S_{AA12}} \tag{34}$$

$$S_{A12}S_{A21} = S_{AA12}\left(1 - S_{A22}^2\right). \tag{35}$$

Once S_{A11} is determined, S_{A22}, and $S_{A12}S_{A21}$ can be easily obtained from (34) and (35). The measurements with reflection standards short, open, and match have been made in the above section. For the TM method, a known match $(S_{M11} = 0)$ is used, and S_{A11} can be determined from (7) easily. For the TS method, solving (5), (34), and (35), we have

$$S_{A11} = \frac{S_{MS11}S_{AA12} - S_{MS11}S_{AA11}S_{S11} + \Delta_{AA}S_{S11}}{S_{AA12} - S_{MS11}S_{S11} + S_{AA11}S_{S11}}. \tag{36}$$

The solution of the TO method is similar to that of the TS method, and will not be given here. From (35), one can see that an uncertainty exists in the phase of S_{A12} and S_{A21}. Assuming that $S_{A21} = |S_{A21}|e^{i(\theta+m\pi)}$, $S_{A12}S_{A21}$ can be expressed as $S_{A12}S_{A21} = |S_{A21}|^2 e^{i(2\theta+2m\pi)}$. The measured phase frequency response is in between $-\pi$ and π. In order to determine m, the measured phase frequency response should be converted to the real one, as shown in Fig. 4. The phase of

$$S_{AA11} = S_{AA22} = \frac{S_{AB11}S_{BC11}S_{CA11} - S_{AB11}\Delta_{BC} + S_{BC22}\Delta_{AB} - S_{CA11}\Delta_{BC}}{S_{BC11}S_{CA11} - S_{CA11}S_{AB22} + S_{BC22}S_{AB22} - \Delta_{BC}} \tag{29}$$

$$S_{AA12} = S_{AA21} = \frac{S_{AB12}S_{BC12}S_{CA12}}{S_{BC11}S_{CA11} - S_{CA11}S_{AB22} + S_{BC22}S_{AB22} - \Delta_{BC}} \tag{30}$$

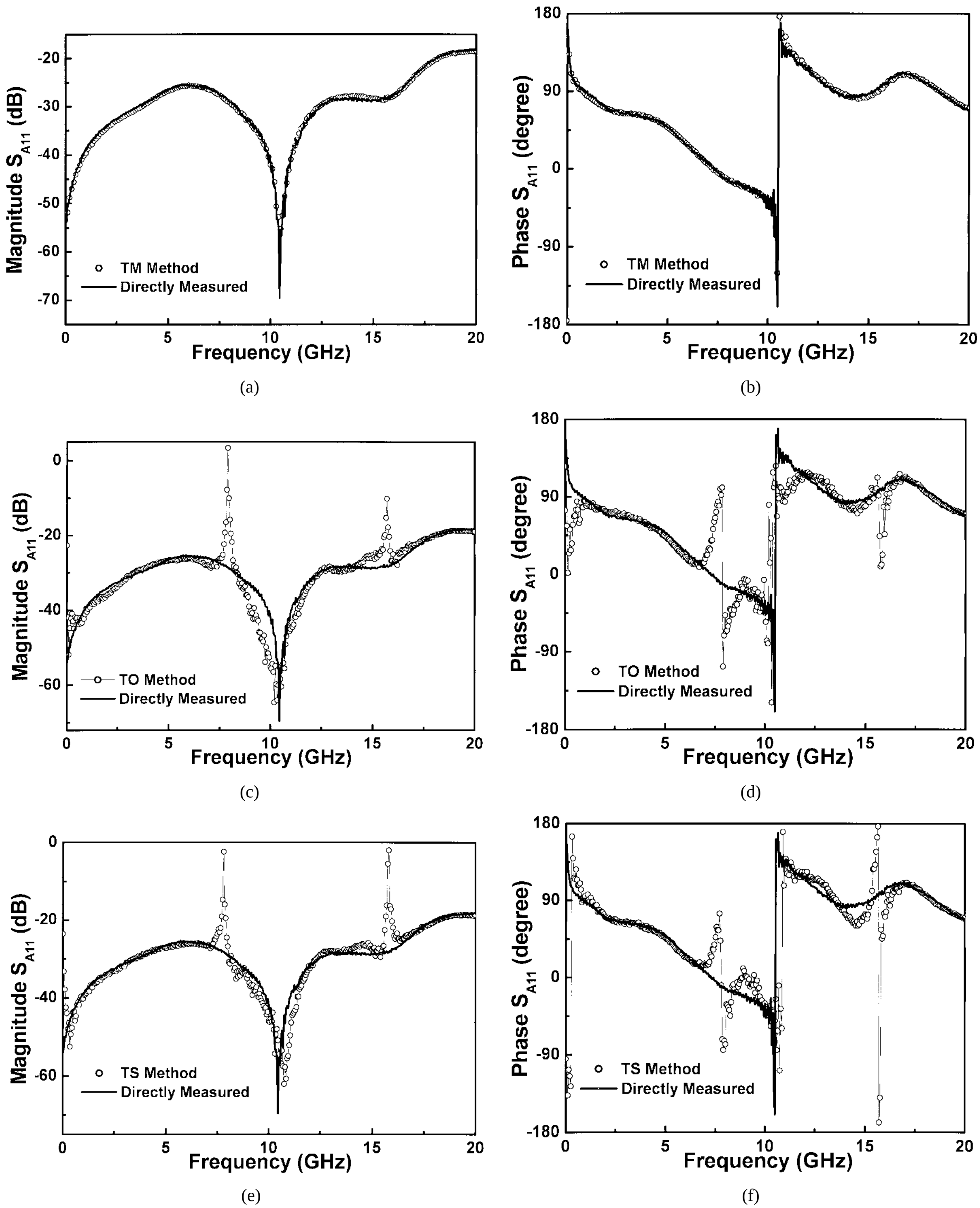

Fig. 6. Measured S-parameter S_{A11} using the TM, TO, and TS methods. Direct measured data are also shown.

S_{A21} can, therefore, be reproduced by dividing the real phase of $S_{A12}S_{A21}$ by two [16].

In order to investigate the reason why the problem of frequency limitation occurs, we substitute (5), (32), and (33) into (36), and express the denominator of S_{A11} as

$$W = S_{AA12} - S_{MS11}S_{S11} + S_{AA11}S_{S11} = \frac{S_{A12}S_{A21}\left(1 - S_{S11}^2\right)}{\left(1 - S_{A22}^2\right)\left(1 - S_{A22}S_{S11}\right)}. \quad (37)$$

The denominator of S_{A11} is given in Fig. 5 as a function of frequency. The measured offset length of the short standard was approximately 9.54 mm. It is predicted that the denominator of S_{A11} approaches zero at frequencies $n \times 7.86$ GHz. This agrees well with the experimental results shown in Fig. 5. Fig. 6 shows the S-parameter S_{A11} obtained using the TM, TS, and TO methods, and the directly measured data are also plotted in this figure for comparison. It can be seen that the TS and TO methods have a frequency limitation. From (37), it follows that if the short standard is replaced by a known termination whose

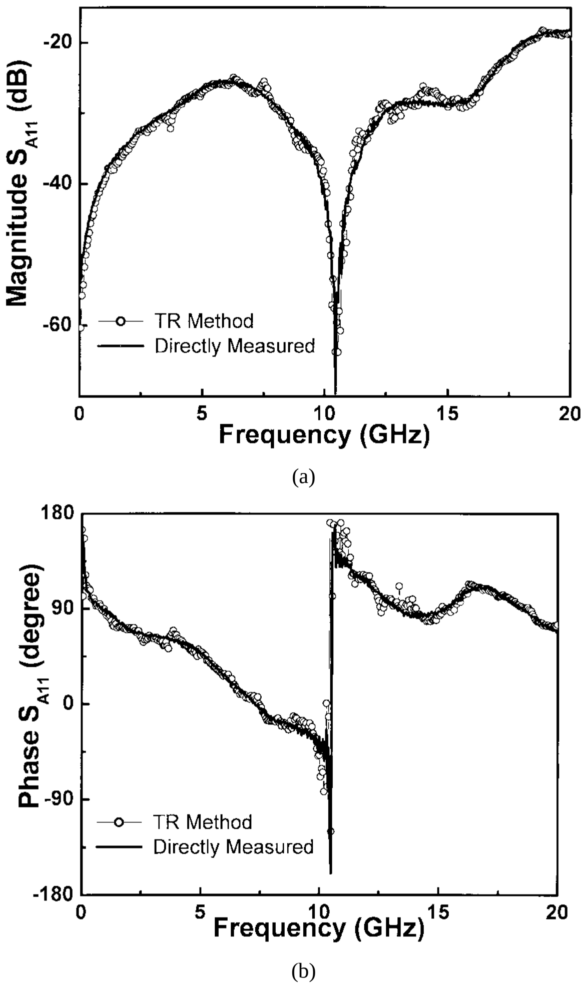

Fig. 7. Measured S-parameter S_{A11} using the TS method, where the short is replaced by a 3-dB attenuator terminated with a short. Direct measurement data are also shown.

reflection coefficient does not approach ± 1, the frequency limitation can be removed. This is supported by the fact that the TM method does not have a frequency limitation. Fig. 7 shows the measured S_{A11} obtained using the TS method, where the short is replaced by a 3-dB attenuator terminated with a short. Figs. 6 and 7 show that there is good agreement between the theory and experimental data.

IV. Discussion and Conclusions

Three standards including at least one transmission standard are needed to calibrate asymmetric test fixtures. In this paper, the TSM method has been taken as an example to investigate the frequency limitation. It has been shown that the conventional TSM method does not have any frequency limitation. The calibration procedure has one redundant equation, which can be used to determine one (unknown) S-parameter of the standards and to improve the accuracy. In principle, any of the S-parameters of the three known standards can be treated as unknown. When the short standard is treated as an unknown, the method reduces to the TMR method [8], and the accuracy of the calibration is improved and there is no frequency limitation [14]. However, when a standard match is treated as an unknown, the problem of frequency limitation appears. Thus, frequency limitation may occur when using the same calibration standards, but a different algorithm. This implies that the frequency limitation can, in general, be avoided by using a different algorithm.

Calibration methods using two transmission-line standards have a frequency limitation. The TSO method has the same problem because the calibration equations obtained with the short and open have correlation with those from the thru at some periodic frequencies. Our investigation on the calibration of asymmetric test fixtures shows that, in certain cases, there may be frequency limitation for the method using only one transmission-line standard with a short (open) and a resistive load.

The TRL is the most precise calibration method. The problem of the frequency limitation can be overcome by using another line standard with different electrical length or by using several line standards similar to the multiline method [9]. In our case, the period of frequency limitation depends on the length of the thru and the offset length of the short. A similar way can also be used to avoid the problem. Since the calibration accuracy becomes worse at some periodic frequencies only, the calibration data around these frequencies can be replaced, e.g., by those obtained using the TSM or TOM method.

We have focused on the TSM method only because the equations obtained from the measurements with an open are similar to those with a short; the theory established here can also be applied to the TOM method.

For the symmetric test fixtures, typical calibration methods using known standards are the TL, TS, TO, and TM methods, and only the TM method does not have an inherent frequency limitation. The TS and TO methods have a frequency limitation because the reflection coefficients of an ideal short or open are close to ± 1. This frequency limitation can be removed when the short or open standard is replaced by a known termination with a reflection coefficient different from ± 1, and there is good agreement between our theoretical and experimental data.

References

[1] R. F. Bauer and P. Penfield, "De-embedding and unterminating," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 282–288, Mar. 1974.

[2] R. A. Speciale, "A generalization of the TSD network-analyzer calibration procedure, covering n-port scattering-parameter measurement, affected by leakage errors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1100–1115, Dec. 1977.

[3] G. F. Engen and C. A. Hoer, "Thru–reflect–line: An improved technique for calibrating the dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987–993, Dec. 1979.

[4] R. P. Meys, "A triple-through method for characterizing test fixtures," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1043–1046, June 1988.

[5] R. R. Pantoja, M. J. Howes, J. R. Richardson, and R. D. Pollard, "Improved calibration and measurement of the scattering parameters of microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1675–1680, Nov. 1989.

[6] D. Williams, "De-embedding and unterminating microwave fixtures with nonlinear least squares," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 787–791, June 1990.

[7] K. J. Silvonen, "Calibration of test fixtures using at least two standards," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 624–630, Apr. 1991.

[8] H. J. Eul and B. Schiek, "A generalized theory and new calibration procedures for network analyzer self-calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 724–731, Apr. 1991.

[9] R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.

[10] K. J. Silvonen, "A general approach to network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 754–759, Apr. 1992.

[11] M. B. Steer, S. B. Goldberg, G. Rinne, P. D. Franzon, I. Turlik, and J. S. Kasten, "Introducing the through-line deembedding procedure," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1992, pp. 1455–1458.

[12] N. H. Zhu and F. Auracher, "Correlation of calibration equations for text fixtures," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1949–1953, Oct. 1999.

[13] N. H. Zhu, "Phase uncertainty in calibrating microwave test fixtures," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1917–1922, Oct. 1999.

[14] N. H. Zhu, Z. Y. Chen, and Y. L. Wang, "New algorithms of the TSM and TOM methods for calibrating microwave test fixtures," *Microwave Opt. Technol. Lett.*, vol. 34, pp. 26–31, 2002.

[15] K. C. Gupta, R. Garg, and R. Chadha, *Computer-Aided Design of Microwave Circuits*. Norwood, MA: Artech House, 1981, pp. 319–322.

[16] Z. Y. Chen, Y. L. Wang, Y. Liu, and N. H. Zhu, "Two-port calibration of the test fixtures with different test ports," *Microwave Opt. Technol. Lett.*, vol. 35, no. 4, pp. 299–302, 2002.

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