Through Symmetric Fixture: A Two-port S parameter Calibration Technique

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A straight-forward procedure for the calibration of a measurement system with symmetric test fixturing is described and experimentally verified.

Introduction

At RF and microwave frequencies the calibration of both vector automatic network analyzers (VANA) and test fixturing is required to accurately determine the scattering parameters of a device under test (DUT). Calibration of a VANA is usually not a problem as it is generally fitted with precision coaxial connectors at the test ports, e.g. APC-3.5, and precisely defined reference standards are available. The conventional OSL (Open Short Load) calibration procedure can then be followed. In situations such as microstrip measurement where conventional standards are not readily available other calibration procedures have been developed. Many of these techniques use variations on the short open and matched load standards as well as some form of delay, e.g. TSD — Through Short Delay [1], TSO — Through-line Short Open [2], TRL — Through Reflect Line [3], LRL — Line Reflect Line [4] and TTT — Triple Through [5]. System calibration using most of these techniques is a two-tier method [2,6] whereby the VANA is first calibrated using OSL and precision standards, and a second calibration performed with the required test fixturing in place and using secondary standards.

While relaxing the requirements on the reference standards, these techniques can still require calibration standards which may be difficult to construct. Most test fixtures can be manufactured such that leakage type errors can be neglected but in general more calibration measurements are required to remove these errors. Calibration techniques can be grouped into three types according to the standards used. These are reflection, reflection/transmission and symmetric where symmetric refers to the fixture characteristics. TSD, TSO, TRL, LRL and TTT are based on reflection/transmission measurements where OSL is based solely on reflection measurements.

The standards needed for OSL are an open, short and load with each standard being placed at the output of the error two-ports, A and B respectively in figure 1. OSL's main advantage is that no distributed standards are used. This allows broadband calibrations to take place. The disadvantage associated with OSL is that all the standards must be assumed ideal or modeled in some way. In addition to this, six measurements are required for complete calibration and this makes OSL the most prone to connector repeatability. The remaining techniques use combinations of reflective and distributed standards and are appropriately termed reflection/transmission types.

TSO uses a length of transmission line, a short and an open as standards. and offers the advantage of not requiring a load standard however it does have some disadvantages. First the length and propagation factor of the transmission line must be known and second the short and open standards are treated just as OSL that is either ideal or modeled. TSO requires five measurements therefor connector repeatability is improved over OSL. Configurations for calibration measurements are shown in figure 2.

TSD is based on both reflection and transmission measurements. The TSD standards are a through connection, short and delay. TSD offers two advantages. A load standard is not required and the total number of calibration measurements is reduced to four. TSD

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is not without disadvantages. The delay must be lossless and reflectionless and not near 180 degrees in the measurement bandwidth and the short circuit is assumed ideal. The configurations for TSD calibration measurements are shown in figure 3.

TRL is an evolution of TSD and requires a through connection, arbitrary reflection and an unknown transmission line length for standards. The advantages include the arbitrary line length which can be lossy and the arbitrary reflection. TRL also does not require a load standard. The number of measurements needed for calibration is four thus offering the same connector repeatability as TSD. Since TRL uses a distributed standard it is subjected to the 180 degree limitation. In addition to this the transmission line must be reflectionless. The calibration configurations are shown in figure 4.

LRL is an extension of TRL but uses an additional line rather than a through connection and the two line standards must be different in length, figure 5. LRL calibration bandwidth is also limited by the 180 degree line restriction with the difference between the length of the line standards being the important dimension. The line standards also need to be reflectionless.

TTT is unique in that it uses a series of two-port cascades to characterize the error networks, figure 6. TTT uses an auxiliary two-port and a matched load for standards and offers the broadband nature of OSL.

If the fixture has some degree of symmetry it is possible to use two standards for calibration of the entire fixture [8]. The standards can be either a through connection and a matched load, figure 7a, or a reflectionless transmission line standard, figure 7b. If the test fixture halves are also symmetrical the calibration standard needed is simply a through connection [9], figure 8.

Here a straight-forward procedure for the calibration of a measurement system with symmetric test fixturing is described and experimentally verified. The only measurement configuration required is a through connection thus, in conformance with the practice of naming calibration procedures, we designate the new technique the TSF — for Through Symmetric Fixture — method.

Symmetric Fixture

When can test fixturing be treated as symmetric? The requirement for symmetric de-embedding as used here is that the test fixture halves are identical and symmetric. This holds at low frequencies when distributed effects are not significant or when the fixtures are electrically small. This also holds at higher frequencies with careful design of the test fixtures so that they are symmetrical. Ideally test fixtures introduce negligible discontinuity and so look like matched transmission lines.

Fixturing for two-port measurements is shown in the through configuration in Figure 9 along with signal flow graph representations of the through measurement and the second-tier error models that must be determined. If **A** and **B** are not identical then a conventional calibration scheme is required to determine the eight error terms, (e_{ija} and e_{ijb}). Practically each fixture is reciprocal ($e_{ij} = e_{ji}$) and so there are only 6 unique error terms. In many situations the fixtures **A** and **B** are identical so that **B** is the port reverse, $\mathbf{A}^{\mathbf{R}}$, of **A**, Figure 10. Now there are 3 unique error terms to be evaluated. If in addition each fixture is symmetric, we have the through configuration and signal flow graph representations of Figure 11 where the scattering matrix of each fixture is

$$[S_A] = \begin{bmatrix} \alpha & \delta \\ \delta & \alpha \end{bmatrix} \tag{1}$$

The configuration for measuring a DUT is shown in figure 12. It is this symmetric identical structure that was addressed in [9] and is considered here.

Method

The determination of the error terms (α and δ) is based upon signal flow graph theory. S parameter measurements of the through connection yield two independent quantities, S_{11} and S_{21}, as $S_{11} = S_{22}$ and $S_{12} = S_{21}$ because of symmetry and reciprocity. This is sufficient to determine $[S_A]$.

The signal flow graph provides two algebraic relationships for the known quantities as functions of the error terms:

$$S_{11} = \delta + \frac{\alpha^2 \delta}{1 - \delta^2} \tag{2}$$

$$S_{21} = \frac{\alpha^2}{1 - \delta^2} \tag{3}$$

Rearranging

$$\delta = \frac{S_{11}}{1 + S_{21}} \tag{4}$$

$$\alpha = \sqrt{S_{21} \frac{b^2 - S_{11}^2}{b^2}} \tag{5}$$

where

$$b = 1 + S_{21} \tag{6}$$

The square root gives two possible solutions and the root choice depends upon the electrical length (L_e) of the through connection. The positive root is valid when

$$n\lambda < L_e < \frac{(2n+1)\lambda}{2} \tag{7}$$

where

$$n = 0, 1, 2, \cdots \tag{8}$$

otherwise the negative root is correct.

Equation (4) contains a singularity that can restrict the use of TSF. When the cascade S_{21} is nearly equal to -1 equation (4) will return invalid results for δ. This singularity can be avoided if the length of the cascade fixture is constructed such that it is not an integer half wavelength ($\frac{n\lambda}{2}$) long at any frequency in a desired measurement range. Similar restrictions exist for the TSD, TRL and LRL techniques.

De-embedding

The device under test (DUT) is inserted between the fixture halves and the embedded S parameters would be measured, $[S_{emb}]$. De-embedding is most easily carried out if cascadable S parameters (T-parameters) are used, obtained by application of the standard S to T transform

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} 1 & -S_{22} \\ S_{11} & S_{12}S_{21} - S_{11}S_{22} \end{bmatrix} \tag{9}$$

so $[S_A]$ becomes $[T_A]$ and $[S_{emb}]$ corresponds to $[T_{emb}]$.

After conversion the embedded DUT is given by the following equation.

$$[T_{emb}] = [T_A][T_{DUT}][T_A] \tag{10}$$

Pre and post multiplication of this equation yields the T-parameters of the DUT

$$[T_{DUT}] = [T_A]^{-1}[T_{DUT}][T_A]^{-1} \tag{11}$$

and thus its S parameters

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{T_{11}} \begin{bmatrix} T_{21} & T_{11}T_{22} - T_{21}T_{12} \\ 1 & -T_{12} \end{bmatrix} \tag{12}$$

Verification

We verify the TSF method by comparing a TSF error model with direct VANA measurement of the test fixture. We also compare TSO and TSF calibrated measurements of a de-embedded DUT. These measurements require sexless connectors at the ports of the fixtures and the DUT. The DUT is a 500 MHz low pass filter and APC-7 connectors are used at the ports of the DUT and fixture halves, A. Each fixture half is comprised of two APC-7 to SMA adapters and a shunt discontinuity. The procedure for measuring and de-embedding the DUT was first to measure the through connected fixture and then insert the DUT and repeat the measurement. A direct measurement of fixture halves and the DUT completes the necessary measurements needed for verification. The TSF fixture error model is compared to direct measurement in figure 13. It is clear to see from figure 13 that both magnitude and phase of S_{11} (δ) and S_{21} (α) agree very well with direct measurements. The final test, comparison of the TSF de-embedded DUT with direct VANA measurement is presented in figure 14 with figure 15 showing an expanded DUT pass band. Again excellent agreement is obtained in both magnitude and phase.

Conclusion

We have presented a straight-forward technique, the TSF method, for determining the scattering parameters of a device measured with a symmetrical test fixture. The single calibration configuration is the through connection. TSF is the appropriate technique to use when the classical reference standards are not readily available and test fixture symmetry can be exploited, or when measurements are made at frequencies low enough that asymmetrical fixture discontinuities can be neglected.

With the single calibration configuration, a simple through, TSF may be preferable to the more elaborate TSD, TRL and LRL techniques which require multiple disconnections and reconnections even at reasonably high frequencies when test fixture symmetry can be exploited.

References

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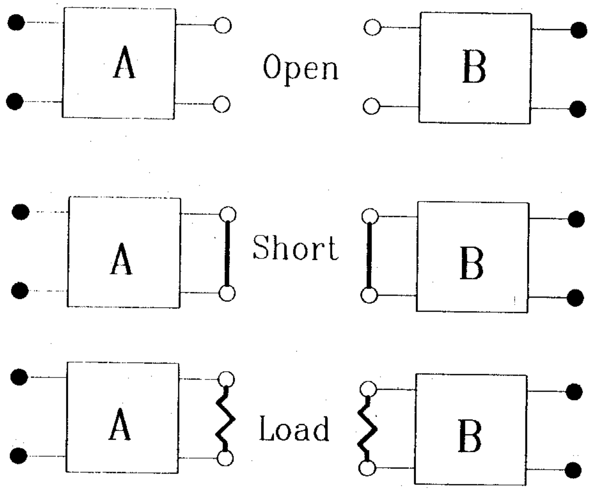


Fig. 1. Configurations for OSL calibration

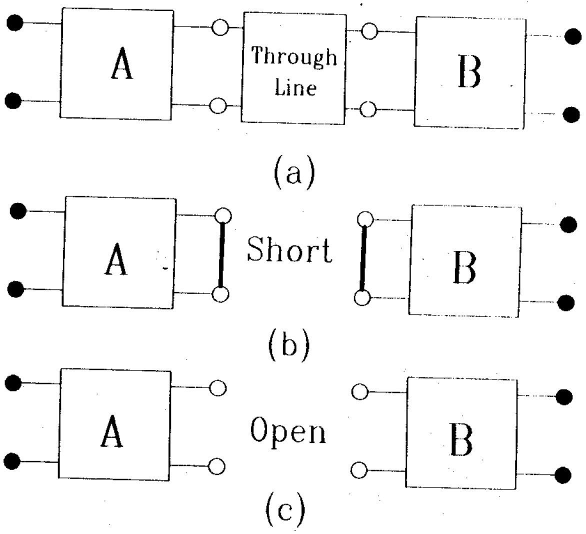


Fig. 2. Configurations for TSO calibration

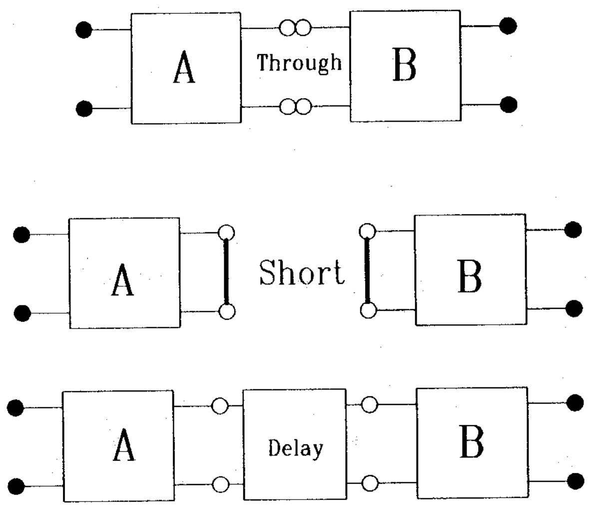


Fig. 3. Configurations for TSD calibration

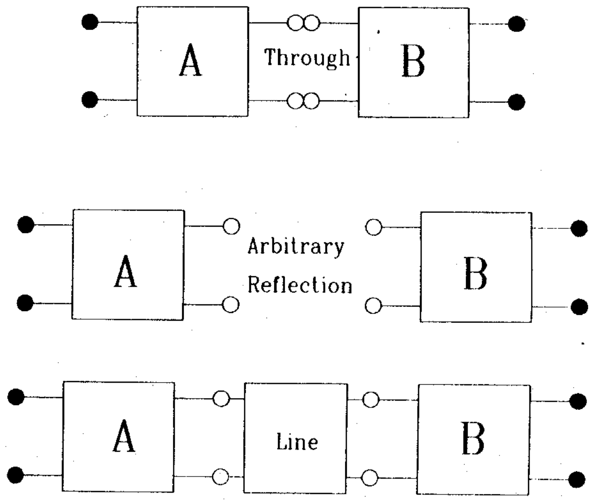


Fig. 4. Configurations for TRL calibration

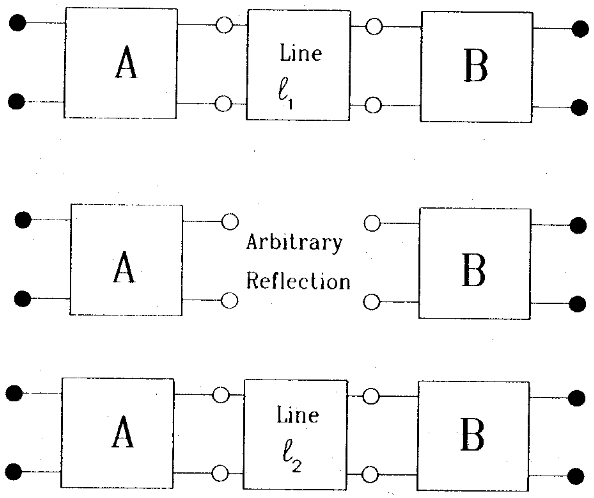


Fig. 5. Configurations for LRL calibration

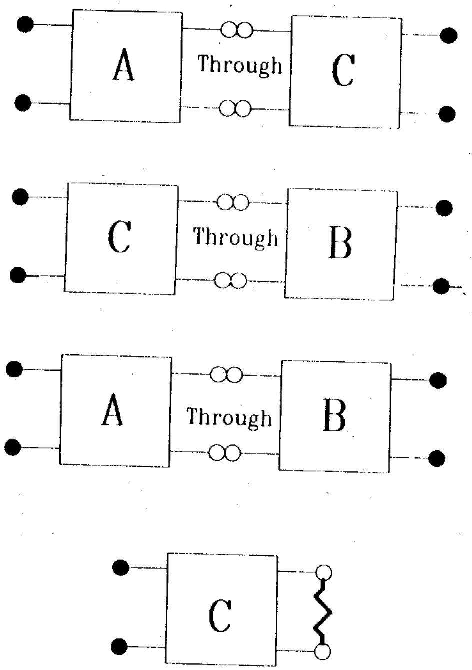


Fig. 6. Configurations for TTT calibration

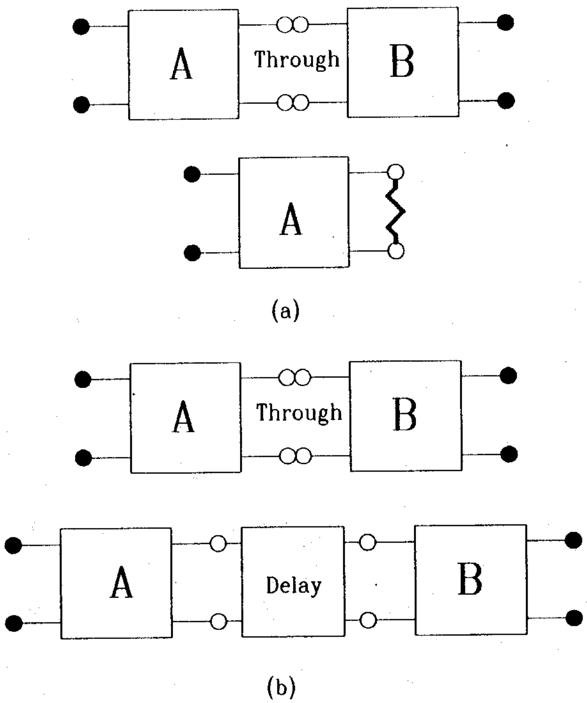


Fig. 7. Configurations for Symmetric fixture calibration

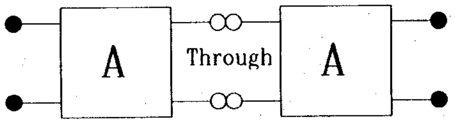


Fig. 8. Configurations for Symmetric fixture with identical halves

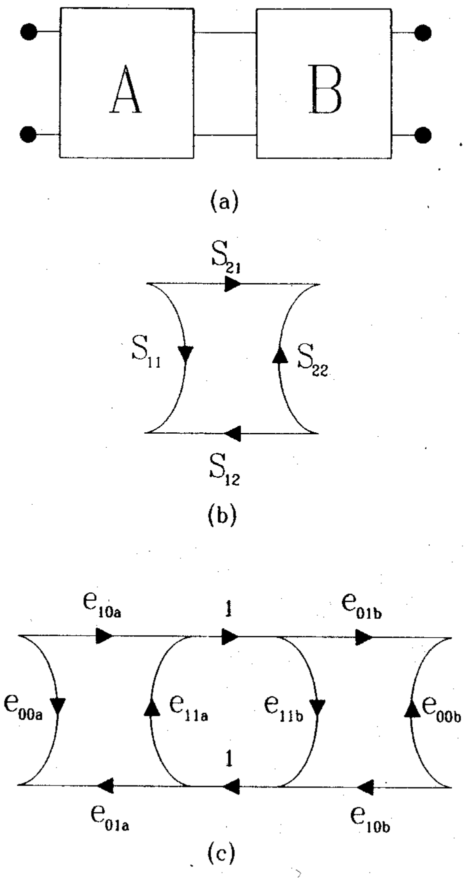


Fig. 9. Through calibration with dissimilar fixtures, (a) configuration, (b) measurement, and (c) signal flow graph with error models.

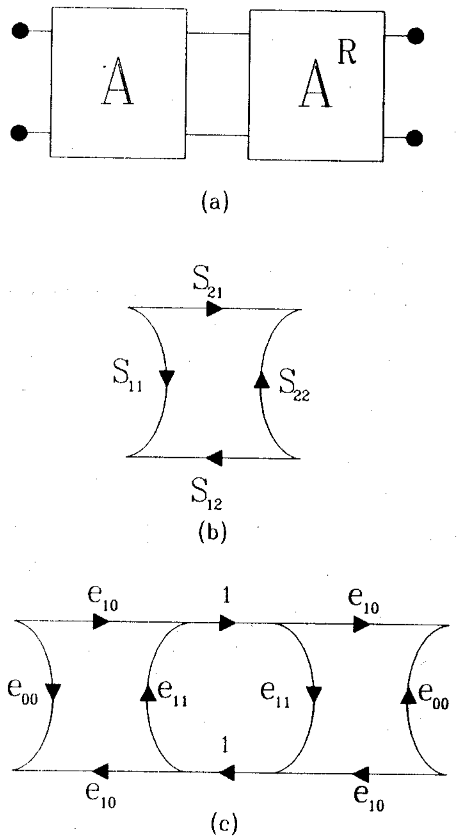


Fig. 10. Through calibration with identical fixtures, (a) configuration, (b) measurement, and (c) signal flow graph with error models.

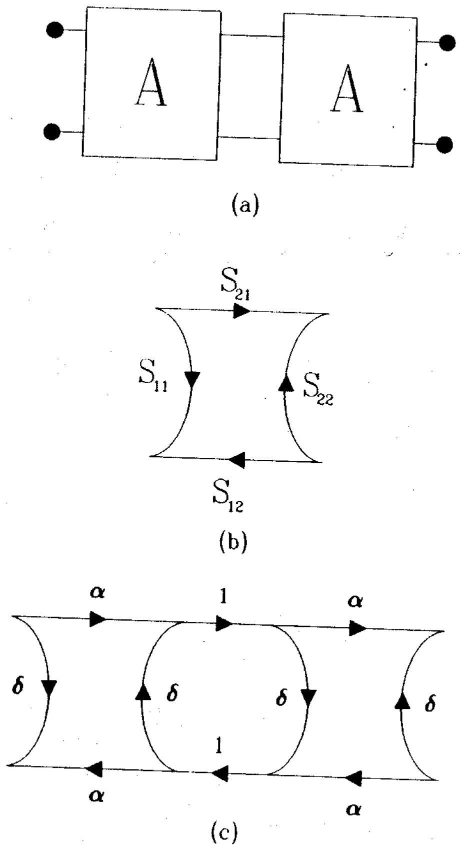


Fig. 11. Through calibration with symmetric and identical fixtures, (a) configuration, (b) measurement, and (c) signal flow graph with error models.

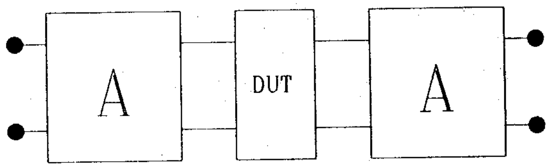
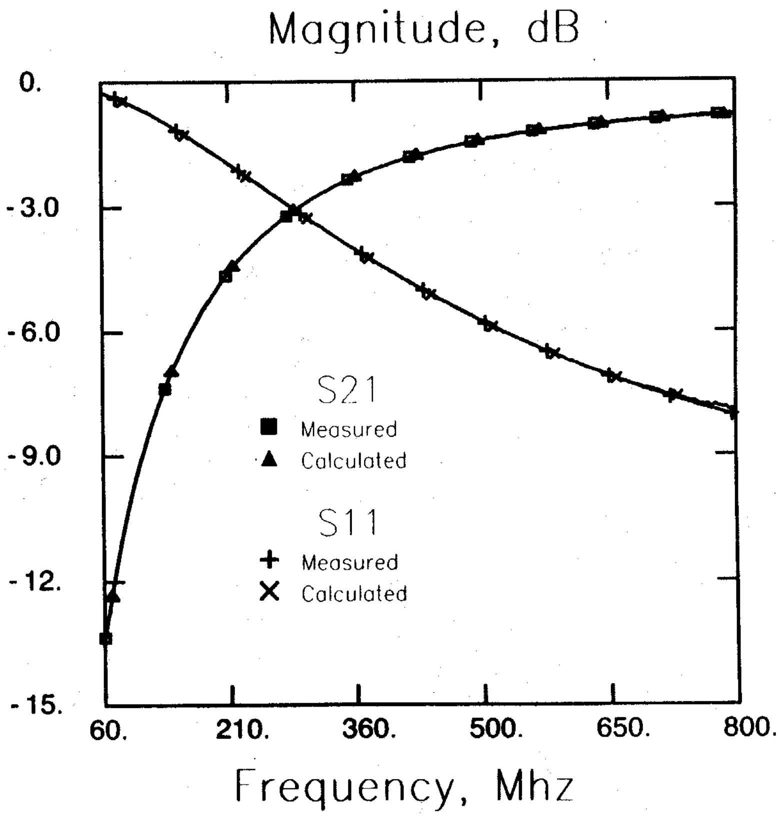
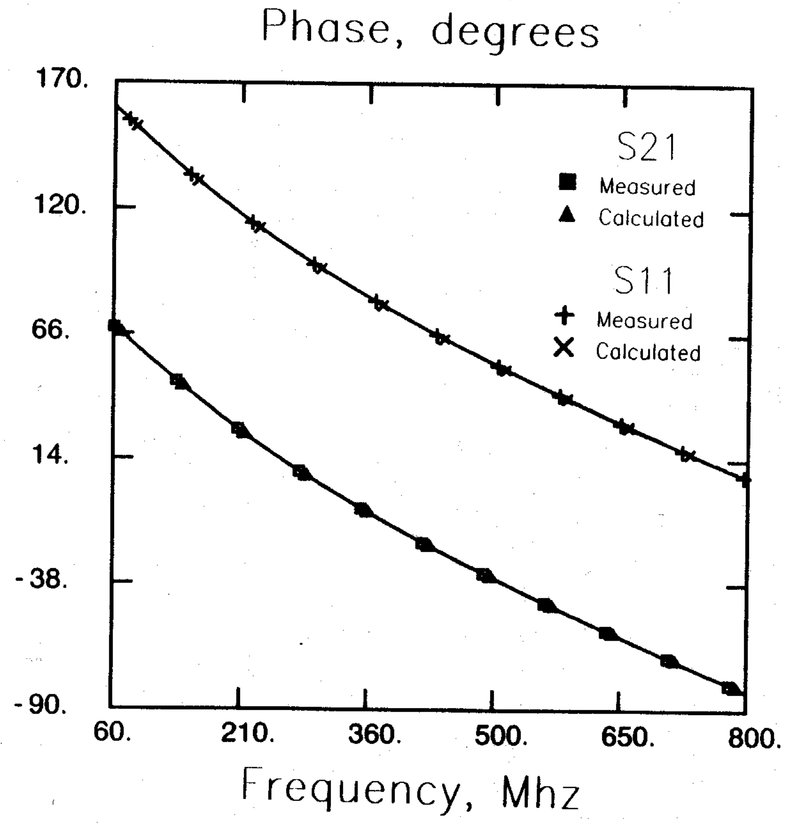


Fig. 12. Configuration for measuring the DUT.



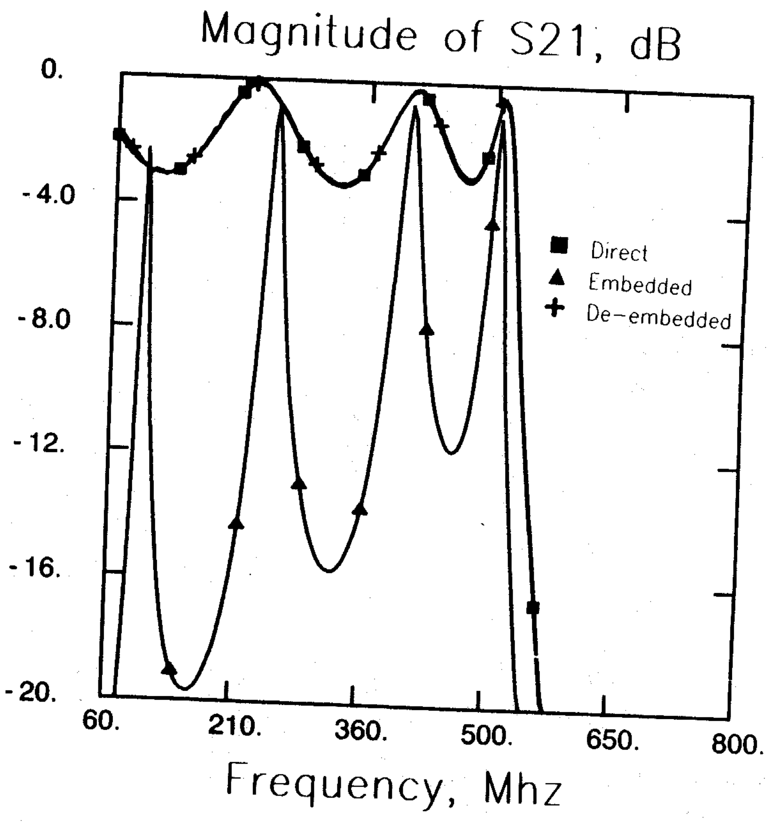
(a)

Fig. 13. Comparison of the S parameters of the fixture half A determined using the TSF technique.



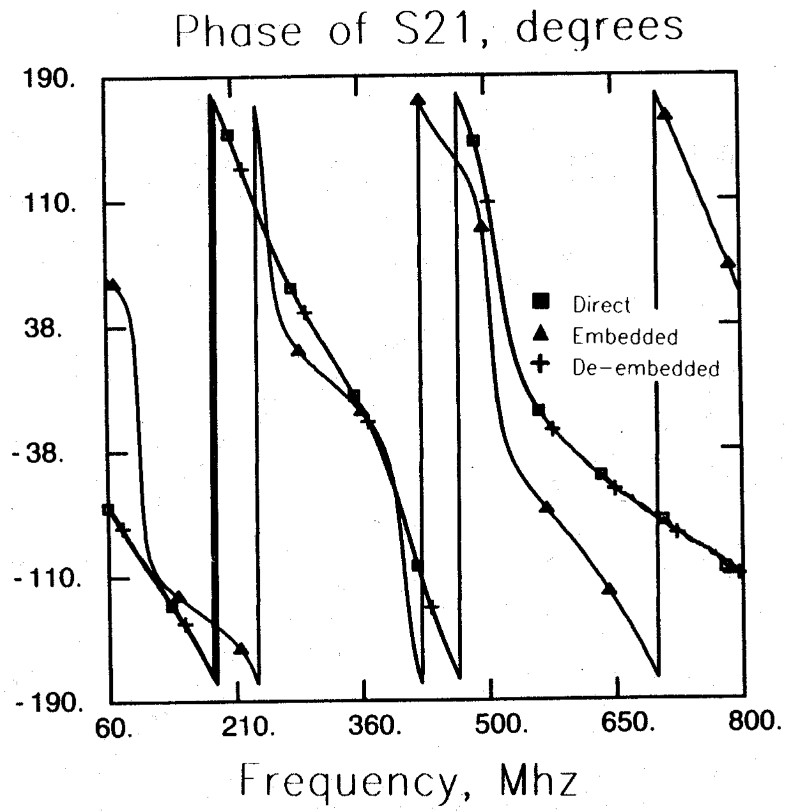
(b)

Fig. 13. Continued.



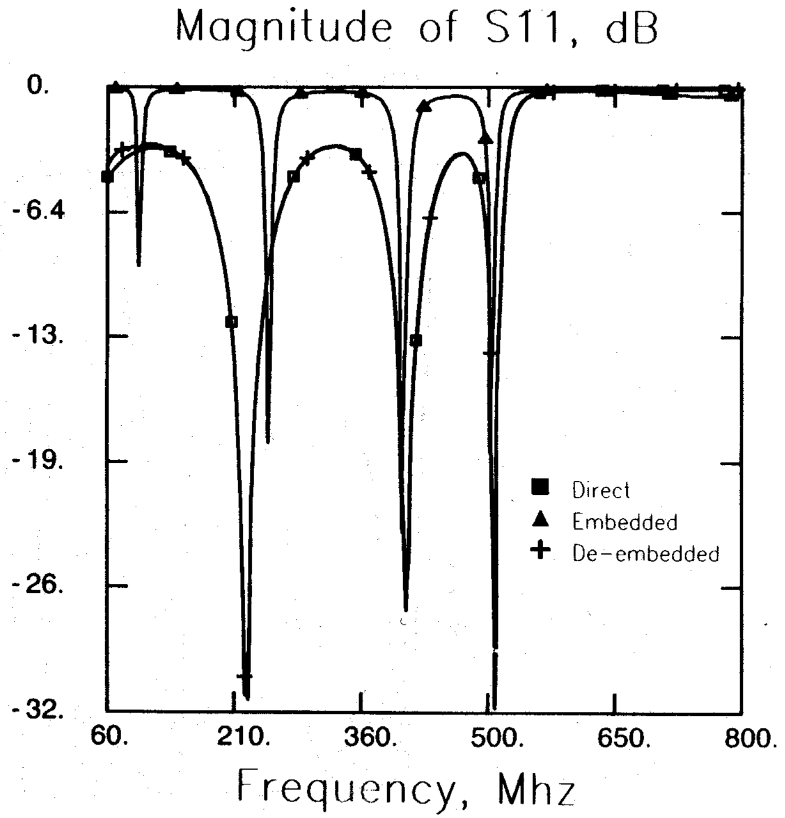
(a)

Fig. 14. Comparison of DUT S parameters with fixtures, DUT de-embedded using TSF, and direct VANA measurement.



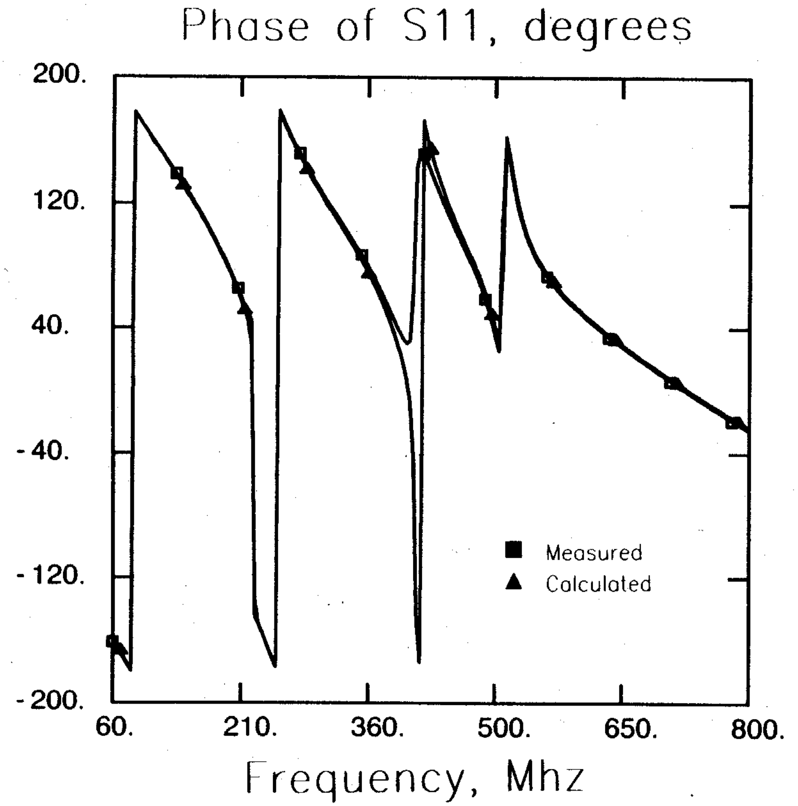
(b)

Fig. 14. Continued.



(c)

Fig. 14. Continued.



(d)

Fig. 14. Continued.

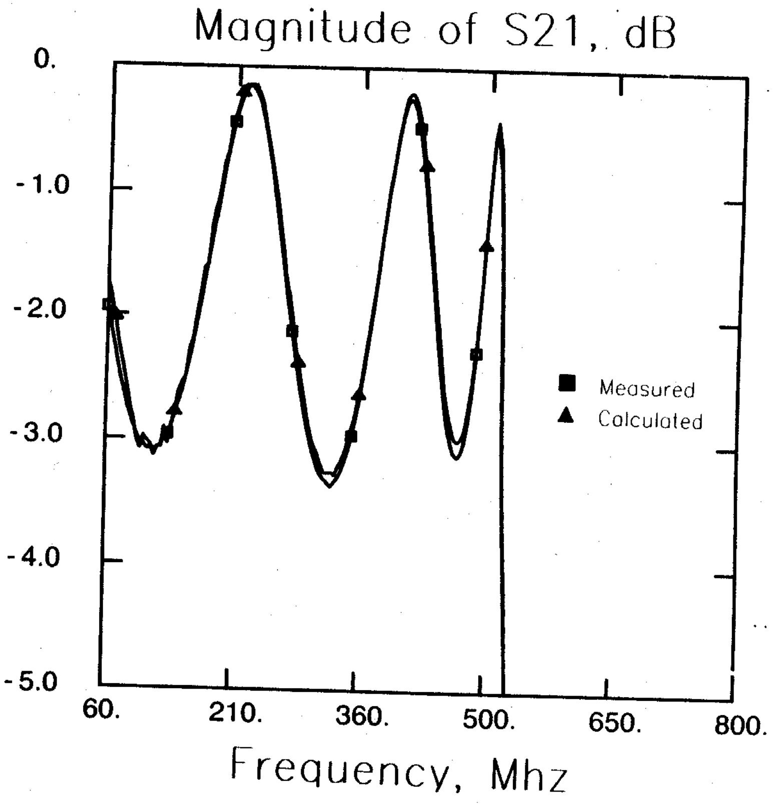


Fig. 15. Comparison of DUT S_{21} de-embedded using TSF and direct VANA measurement.