Research on Calibration Algorithm of Non-coaxial RF Device Test Fixture

CHANG Liang¹, SUN Qi Lin², PENG Yi Wei¹, XIANG Yi³, WANG Zhuang², LIU Jun Rong¹

¹The electronic Fifth Institute of the Ministry of industry and information technology, Guangzhou, Guangdong, 510610, China
²Guilin University Of Electronic Technology, Gui Lin, Guangxi, 541004, China
³Yue Yang Vocational Technical College, Yue Yang, Hunan, 414000, China

Abstract. With the rapid development of RF devices, the requirements for their testing techniques are becoming stricter and stricter. Due to the large errors introduced by the test fixtures during the testing process, it is necessary for a suitable calibration algorithm to eliminate them. For eliminating errors, in this paper, the SOLT calibration algorithm and the TRL calibration algorithm are selected for mathematical derivation, and establish a mathematical model. According to the mathematical derivation of the calibration algorithm and the simulation using Matlab, consequently, the correctness of the SOLT calibration algorithm and the TRL calibration algorithm is verified. It is concluded that the SOLT calibration algorithm is more suitable for the low frequency bands test of the non-coaxial RF device test fixture, while the TRL calibration algorithm is more suitable for high frequency bands test of non-coaxial RF device test fixture.

1. Introduction
At present, the test device for the S parameter of the RF device is a vector network analyser (VNA), and the test connection of the VNA is generally a coaxial interface. However, the input/output ports of the device are generally not coaxial. Therefore, when testing the S-parameters of the device, designing corresponding test fixture for the pins of the non-coaxial RF device to convert the pins of the non-coaxial RF device into the coaxial interface through the micro-strip line, and then it can be directly connected with the coaxial interface of the VNA to measure the S parameter[1]. Compared with DC and low frequency devices, the operating wavelength of RF microwave devices is very short, and the physical size is also very small. The error introduced by the test fixture will also have a great impact on the test results of the device parameters, which often makes the test results inaccurate. It is generally called the Fixture Effect[1].

If you want to obtain the accurate parameters of the device under test, you need to carry out precise and scientific design of the test fixture, including complete the circuit and mechanical design of the RF-transmission conversion between the coaxial to transmission line and the transmission line to pin. Then, study corresponding calibration algorithm to analyse the error caused by the access of the test fixture. Finally, the error is eliminated by SOLT (Short-Open-Load-Thru), TRL (Thru-Reflect-Line) and other de-embedded algorithms, so that the test fixture can accurately test the S parameters of the RF device to complete the performance of the device[1].

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The standard interface provided by the VNA has various types of coaxial interfaces, and generally has BNC (Bayonet Nut Connector), SMA (Stone Mastic Asphalt), N and so on. In the actual test work, since the pin of the device under test and the input/output port structure of the instrument are different, it is necessary to feed-in and output the signal through the measuring fixture. Due to the high electrical performance requirements of the measuring fixture, it is necessary to achieve a smooth transition of the signal, which requiring the measuring fixture to have small signal reflection in the working frequency band of the device under test, low insertion loss, and no absorption peak and reflection peak in the band\(^{(1)}\). These series of requirements need to be designed with appropriate calibration algorithms to better calibrate non-coaxial RF device test fixtures. Therefore, the study of the test fixture calibration algorithm for non-coaxial RF devices is very important to reality.

2. Principle Analysis of Vector Network Analyzer

The VNA is the main equipment for the calibration of the non-coaxial RF device test fixture. As shown in Figure 1, it is the internal structure block diagram of the VNA. It can be seen that the excitation signal source, the signal separation device (directional coupler and power divider), receiver, data processing and display module composition \(^{(1)}\). Non-coaxial RF device calibration principle: The standard RF device (standard part) with known characteristics is used to connect to the measurement fixture, and the parameters of the measurement fixture are reversed by the test results of the standard parts, and then the parameters of the test fixture are obtained. The precision and accuracy of the standard parts become the key point for measuring the accuracy of the fixture parameters. The higher the precision of the standard parts, the more accurate the results will be.

![Figure 1. Internal block diagram of the VNA](image)

From the internal network diagram of the VNA, it can be seen that the introduced error sources mainly include the instrument itself and the test fixture. The system errors caused by the VNA mainly include directional error, isolation error, source impedance matching error, load impedance matching error, transmission frequency response error and reflection frequency response error. However, there are twelve kinds of error sources for the two-port test fixture.

3. Non-coaxial RF device calibration algorithm

Because of the access of the test fixture, errors are bound to introduce in the VNA test. According to the model of error parameters, it is analyzed that there are a total of 12 errors in the vector network analysis test, and there are 6 errors in the forward path and the backward path respectively\(^{(1)}\). Therefore, in the calibration process, the error items need to be eliminated. Among the methods to eliminate error terms, SOLT calibration algorithm and RTL calibration algorithm are typical.
3.1 Research on SOLT Calibration Algorithm

VNA has two calibration methods, which includes single-port calibration and dual-port calibration, while the calibration of non-coaxial RF device test fixture usually adopts dual-port calibration, as shown in figure 2.

![Signal flow diagram of 12 errors](image)

According to the signal flow diagram of 12 errors, the relationship between the scattering parameters obtained by the test and the true scattering parameters of the device under test containing the error term can be calculated by using the Mason formula, which can be obtained [1].

\[
S_{11R} = \frac{A(1 + DE_{SR}) - BCE_{LF}}{d} \\
S_{22R} = \frac{D(1 + AE_{SF}) - BCE_{LR}}{d} \\
S_{12R} = \frac{C(1 + A(E_{SF} - E_{LR}))}{d} \\
S_{21R} = \frac{B(1 + D(E_{SR} - E_{LF}))}{d}
\]

Among them:

\[
A = \frac{S_{11T} - E_{DF}}{E_{RF}}, \quad D = \frac{S_{22T} - E_{DR}}{E_{RR}}, \quad B = \frac{S_{21T} - E_{XF}}{E_{TF}}, \quad C = \frac{S_{12T} - E_{XR}}{E_{TR}}
\]

\[d = (1 + AE_{SF})(1 + DE_{SR}) - BCE_{LF}E_{LR}\]

During the test process, the short-circuit calibration kit (Short), the open-circuit calibration kit (Open), the load calibration kit (Load), and the straight-through calibration kit (Thru) with known characteristic parameters are respectively connected to the network under test for testing. The error is calibrated and corrected by the test results. According to the signal flow diagram of the error model of the short-circuit calibration kit, the error model of the open-circuit calibration kit, the error model of the load calibration kit, and the error model of the straight-through calibration kit, the following formula can be obtained:
\[ T_1 = S_{11T} = E_{DF} + \frac{E_{RF}}{1 - E_{SF}} \]  
\[ T_2 = S_{22T} = E_{DR} + \frac{E_{RR}}{1 - E_{SR}} \]  
\[ T_3 = S_{11T} = E_{DF} + \frac{-E_{RF}}{1 + E_{SF}} \]  
\[ T_4 = S_{22T} = E_{DR} + \frac{-E_{RR}}{1 + E_{SR}} \]  
\[ T_5 = S_{11T} = E_{DF} \]  
\[ T_6 = S_{22T} = E_{DR} \]  
\[ T_7 = S_{21T} = E_{XF} \]  
\[ T_8 = S_{12T} = E_{XR} \]  
\[ T_9 = S_{12T} = E_{XR} + \frac{E_{TR}}{1 - E_{SR}E_{LR}} \]  
\[ T_{10} = S_{21T} = E_{XF} + \frac{E_{TF}}{1 - E_{SR}E_{LF}} \]  
\[ T_{11} = S_{11T} = E_{DF} + \frac{E_{LF}E_{RF}}{1 - E_{SR}E_{LF}} \]  
\[ T_{12} = S_{22T} = E_{DR} + \frac{E_{RR}E_{LR}}{1 - E_{SR}E_{LR}} \]

According to error models, 12 errors that need to be solved can be obtained as follows:

\[ E_{DF} = T_5, \quad E_{RF} = \frac{2(T_2 - T_3)(T_3 - T_5)}{T_3 - T_1}, \quad E_{SF} = \frac{T_3 + T_5 - 2T_2}{T_3 - T_1} \]
\[ E_{XF} = T_6, \quad E_{LF} = \frac{T_{10} - T_3}{E_{SR}(T_{10} - T_3) + E_{RF}}, \quad E_{TF} = (T_9 - T_6)(1 - E_{SR}E_{LF}) \]
\[ E_{DR} = T_7, \quad E_{RR} = \frac{2(T_7 - T_2)(T_4 - T_7)}{T_4 - T_2}, \quad E_{SR} = \frac{T_4 + T_5 - 2T_7}{T_4 - T_2} \]
\[ E_{XF} = T_8, \quad E_{LR} = \frac{T_{12} - T_7}{E_{SR}(T_{12} - T_7) + E_{RR}}, \quad E_{TR} = (T_{11} - T_8)(1 - E_{SR}E_{LR}) \]

At this point, the results of 12 errors were obtained. 12 errors are substituted into (1) ~ (4), which can complete the calibration of the scattering parameters of the measured RF device by the SOLT method.
3.2 Research on TRL Calibration Algorithm

The S parameter can be converted into the transmission matrix-R matrix based on the error network, which can be obtained as follows [8]:

\[
R = \frac{1}{r_{22} \rho_{22}} \left[ \begin{array}{cc}
1 & -b \\
-c & a \\
\end{array} \right] \left[ \begin{array}{cc}
1 & -\beta \\
-\gamma & \alpha \\
\end{array} \right] T \left[ \begin{array}{cc}
1 & -b \\
-\gamma & \alpha \\
\end{array} \right]
\]

(17)

Among them:

\[
R_A = \left[ \begin{array}{cc}
r_{11} & r_{12} \\
r_{21} & r_{22} \\
\end{array} \right] = r_{22} \left[ \begin{array}{cc}
a & b \\
c & a \\
\end{array} \right]
\]

(18)

\[
R_B = \left[ \begin{array}{cc}
\rho_{11} & \rho_{12} \\
\rho_{21} & \rho_{22} \\
\end{array} \right] = \rho_{22} \left[ \begin{array}{cc}
\alpha & \beta \\
\gamma & 1 \\
\end{array} \right]
\]

(19)

\[
R_A^{-1} = \frac{1}{r_{22}} \left[ \begin{array}{cc}
1 & -b \\
-c & a \\
\end{array} \right]
\]

(20)

\[
R_B^{-1} = \frac{1}{\rho_{22}} \left[ \begin{array}{cc}
1 & -\beta \\
-\gamma & \alpha \\
\end{array} \right]
\]

(21)

Although there are eight errors, after the solution, \(r_{22}\rho_{22}\) can be combined into one error, that is, the values of \(a, b, c, \alpha, \beta, \gamma, r_{22}\rho_{22}\) can be used to correct the systematic error introduced during the test, and the real S parameter of the device under test can be obtained.

The results of the measurement of the through-pass and the delay-line are represented by the R matrix, the measurement result of the through-pass kit is represented by \(R_{TH}\), and the measurement result of the delay-line is represented by \(R_{D}\). By defining a formula \(T = R_D R_{TH}^{-1}\), the following formula can be obtained:

\[
TR_A = R_D R_L
\]

(22)

The T matrix can be written as:

\[
T = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}
\]

(23)

Meanwhile, RL has the following formula:

\[
R_L = \begin{bmatrix} e^{+\gamma t} & 0 \\ 0 & e^{+\gamma t} \end{bmatrix}
\]

(24)

Further, the following can be obtained:

\[
\begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} a & b \\ c & 1 \end{bmatrix} = \begin{bmatrix} a & b \\ c & 1 \end{bmatrix} \begin{bmatrix} e^{+\gamma t} & 0 \\ 0 & e^{+\gamma t} \end{bmatrix}
\]

(25)

Since \(e^{+\gamma t}\) is not 1, \(a/c\) and \(b\) are different roots of the unary quadratic equation, and the following can be obtained:

\[
\frac{a}{c} = \frac{r_{11}}{r_{21}} = S_{11} - \frac{S_{12}S_{21}}{S_{22}}
\]

(26)

\[
b = r_{12} = S_{11}
\]

(27)

It can be seen that, \(|S_{12}|<<1, |a/c|>>1\), that is, \(|b|<<|a/c|\). So the choice of root is determined.
Return to the test results of the Thru calibration piece, the following can be obtained:

\[
\begin{bmatrix}
\alpha \\
\beta \\
\gamma \\
1
\end{bmatrix} = \frac{1}{a-bc} \begin{bmatrix}
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22}
\end{bmatrix}
\]  \quad (28)

\[
r_{22}\rho_{22} = \frac{a R_{T22} - c R_{T12}}{a - bc} = \frac{a}{c} \frac{R_{T22} - R_{T12}}{a - b}
\]  \quad (29)

\[
\begin{bmatrix}
\alpha \\
\beta \\
\gamma \\
1
\end{bmatrix} = \frac{1}{a R_{T22} - c R_{T12}} \begin{bmatrix}
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22} \\
R_{T11} - bR_{T21} & R_{T12} - bR_{T22}
\end{bmatrix}
\]  \quad (30)

\[
\gamma = \frac{a}{c} \frac{R_{T22} - R_{T12}}{a - b}
\]  \quad (31)

\[
\beta = \frac{R_{T12} - bR_{T22}}{R_{T11} - bR_{T21}}
\]  \quad (32)

\[
\alpha a = \frac{R_{T11} - bR_{T21}}{R_{T22} - \left(\frac{c}{a}\right)R_{T12}}
\]  \quad (33)

It is found that the error is \(\beta/a, \gamma, r_{22}\rho_{22} \text{ and } \alpha a\). It is necessary to find \(a\) to complete the solution of 7 error terms. Set \(A\) - the error reflection measurement - be \(\omega_1\), and set \(B\) - the error reflection measurement - be \(\omega_2\).

\[
\omega_1 = \frac{a\Gamma R + b}{c\Gamma R + 1}
\]  \quad (34)

\[
\omega_2 = \frac{a\Gamma R - \gamma}{\beta\Gamma R - 1}
\]  \quad (35)

Further, the following can be obtained:

\[
a = \frac{\omega_1 - b}{\Gamma R \left(1 - \omega_1 \frac{c}{a}\right)}
\]  \quad (36)

\[
\alpha = \frac{\omega_1 + \gamma}{\Gamma R \left(1 + \omega_2 \frac{\beta}{\alpha}\right)}
\]  \quad (37)

In the TRL method of solving the error term, the five error terms, including \(a, c, \alpha, \beta, \gamma\) are all attributed to the solution of the error term \(a\). In the TRL method of solving the error term, \(b\) and \(a/c\) are first calculated. Defining a formula \(N = R_{II}^{-1} R_D\), the following formula can be obtained:

\[
R_B N = R_I R_B
\]  \quad (38)

The \(N\) matrix can be written as:
Combining with equations (26) and (27), the determined values of \( (\alpha/\beta) \) and \( \gamma \) can be obtained. Introducing the test value of reflect and combining it with equations (34) and (35), it can be concluded that:

\[
\Gamma_R = \frac{1}{\beta} \left( \frac{a}{c} + \frac{\omega_1}{\omega_2} \right)
\]

(40)

\[
\Gamma_R = \frac{1}{\beta} \left( \frac{\omega_1}{\omega_2} - \frac{\alpha}{\beta} \right)
\]

(41)

Multiply equation (40) by equation (41), it can be concluded that:

\[
\Gamma_R = \left( \frac{b - \omega_1}{a - \omega_2} + \frac{\alpha R_{TH22} - R_{TH12}}{\omega_1 - \omega_2 - b R_{TH22}} \right)^{\frac{1}{2}}
\]

(42)

Because of the value of \( \Gamma_R \) is positive and theoretically close to 1, so it is not necessary to consider the problem of root selection. At the same time, substituting equation (42) into equations (40) and (41), \( \beta \) and \( c \) can be obtained, that is, \( a \) and \( \alpha \) can be obtained. So far, seven errors are obtained and the TRL algorithm calibration can be completed.

4. Simulation verification of non-coaxial RF device test fixture calibration algorithm

The more common calibration methods are SOLT calibration method and TRL calibration method. Since the application range of SOLT calibration method and TRL calibration method is different, in order to ensure good calibration effect, the appropriate calibration algorithm should be selected according to the needs. Therefore, the SOLT algorithm and the TRL algorithm are deduced respectively by using the parameters of S calibration kit, and Matlab is used for simulation verification.

4.1 SOLT calibration algorithm simulation verification

In order to verify the correctness of the SOLT algorithm, the de-embedded calibration algorithm of the SOLT is used to verify the algorithm by Matlab. The simulation results are shown in figure 3. Due to unaffected by external environment and calibration kits in the simulation environment. The uncalibrated test data only contains the systematic error caused by the microstrip line-coaxial structure and the microstrip line itself, so that the resonance point of the test data and the phase of the test result are shifted to different degrees. After the test data is calibrated, The position of the resonance point and the phase of the test data are calibrated.
4.2 TRL calibration algorithm simulation verification

In order to verify the correctness of the TRL algorithm, the calibration algorithm is implemented by Matlab. The parameters are derived by using the 3D calibration model built in HFSS. The 2.5GHz~12.5GHz is selected as the verification frequency, that is, Line3 is selected as the delay-line calibration kit. The Murata’s 1pF capacitor is still used as the device under test. The simulation results are shown in figure 5. Figure 6 is a comparison of the S parameters of the Murata’s official 1pF capacitor with the official data after the TRL calibration. From the results of the TRL calibrated data compared with the official data, it can be seen that the calibrated data is consistent with the data of
Murata’s official 1pF capacitor, both in amplitude and phase. Thus, the superiority of the TRL calibration algorithm is verified, and it is more suitable for high frequency bands.

5. Conclusion
In order to eliminate the error introduced by the non-coaxial RF device test fixture, in this paper, the SOLT calibration algorithm and the TRL calibration algorithm is utilized. What’s more, the simulation results verify the correctness of the two algorithms applied to the non-coaxial RF device test fixture calibration. Finally, it is concluded that the SOLT calibration algorithm is suitable for low frequency bands test, and the TRL calibration algorithm is suitable for high frequency bands test. The research on the calibration algorithm of non-coaxial RF device test fixture provides a theoretical basis for the design of non-coaxial RF device test fixture.
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