# Influence of calibration parameters on extracting S-parameters of microwave probe

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**Abstract**

The microwave probe is an important measurement fixture for monolithic microwave integrated circuit (MMIC). The S-parameter of the probe significantly affects the accuracy of the chip test in the de-embedding test. In this paper, a probe S-parameter extraction method is proposed by considering the influence of all calibration parameters. The results of different microwave probes and calibration kits are compared. The effect of each calibration parameter on the S-parameter of the probe is evaluated.

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The microwave probe is an important measurement fixture for monolithic microwave integrated circuit (MMIC). The *S*-parameter of the probe significantly affects the accuracy of the chip test in the de-embedding test. In this paper, a probe *S*-parameter extraction method is proposed by considering the influence of all calibration parameters. The results of different microwave probes and calibration kits are compared. The effect of each calibration parameter on the S-parameter of the probe is evaluated.

*Introduction:* Since the advent of microwave probe in the 1980s, it has become an important tool for the detection technology of semiconductor integrated circuits and discrete devices on wafer. Its own *S*-parameter significantly affects the accuracy of the wafer test. Moreover, in many wafer test scenarios, if the complete *S*-parameter of the microwave probe is known in advance, it can be directly embedded, eliminating the probe calibration step, no need to use the specialized on-wafer calibration kits, reducing testing costs. Imprecise probe *S* parameters affect the test results. The self-evaluation of microwave probe is also an important issue for manufacturers. Therefore, it is necessary to study how to precisely measure the *S*-parameter of microwave probes.

At present, the extraction method of probe parameters is based on SOLT (Short-Open-Load-Through) calibration [1] [4], and TRL(Through-Reflection-Line) calibration for waveguide probes[2] [4], LRRM (Line-Reflection-Reflection-Match) is also an optional calibration method [3]. In the current on-wafer test, the commercial calibration kit can only give calibration parameters for specific probes. The gold layer damages the calibration kit, and different binding positions of the probes and other circumstances can also cause calibration parameters to change[5] [6]. However, the above study did not investigate the change of results caused by the change of calibration parameters. It is necessary to study the change of calibration parameters for *S*-parameter extraction of the probe.

*Method*: Extended OSL is an algorithm for calculating *S* parameters of microwave probe based on SOLT.

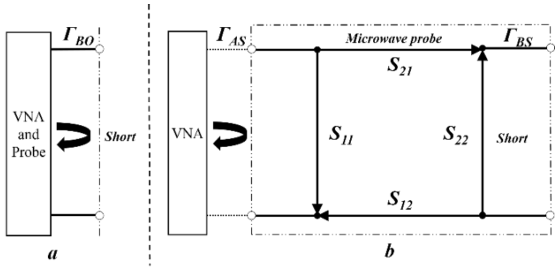


*Fig. 1 Schematic diagram of short-circuit situation. (a) measurement port A, (b) measurement port B.*

Taking the short-circuit situation as an example, as shown in Fig. 1 (a), the measurement port is moved in front of the probe connector by coaxial calibration. This measurement port is called A. Then, the measure standard short-circuit on the wafer calibrator, and the reflection parameter at this time is identified as $\Gamma_{AS}$, as shown in Fig. 1 (b). The measuring port is moved to the tip of the probe with the on-wafer calibrator, calling this measurement port B, measure the same standard short-circuit, and the reflection parameter in this case is $\Gamma_{BS}$; the correlation between $\Gamma_{AS}$ and $\Gamma_{BS}$ and S parameter($S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$) of the microwave probe is [2-3]:

$$\Gamma_{AS} = S_{11} + \frac{S_{21}S_{12}\Gamma_{BS}}{1-S_{22}\Gamma_{BS}} \ . \tag{1}$$

Analogously, the equation of the standard open-circuit reflection $\Gamma_{AO}$ for measurement port A and the standard open-circuit reflection $\Gamma_{BO}$ for measurement port B and parameter S is expressed as eq. 4; The equation of the standard load-circuit reflection parameter $\Gamma_{AL}$ for measurement port A and the standard load-circuit reflection $\Gamma_{BL}$ for measurement port B and parameter *S* are expressed as, respectively

$$\Gamma_{AO} = S_{11} + \frac{S_{21}S_{12}\Gamma_{BO}}{1-S_{22}\Gamma_{BO}} \ , \tag{2}$$

$$\Gamma_{AL} = S_{11} + \frac{S_{21}S_{12}\Gamma_{BL}}{1-S_{22}\Gamma_{BL}} \ . \tag{3}$$

First, considering the most ideal case, where the reflected standard component provides an ideal open circuit ($\Gamma_{BO} = 1$), an ideal short circuit ($\Gamma_{BS} = -1$) and an ideal load ($\Gamma_{BL} = 0$). The following eq. 6-8 can be obtained, identified as method 1, given as

$$S_{11} = \Gamma_{AL} \qquad , \tag{4}$$

$$S_{22} = \frac{\Gamma_{AO}+\Gamma_{AS}-2\Gamma_{AL}}{\Gamma_{AO}-\Gamma_{AS}} \quad , \tag{5}$$

$$S_{12}S_{21} = \frac{2(\Gamma_{AS}-\Gamma_{AL})(\Gamma_{AO}-\Gamma_{AL})}{\Gamma_{BO}(\Gamma_{AS}-\Gamma_{AO})} \tag{6}$$

The mostly used equation is the following eq. 4-6, and only the ideal load ($\Gamma_{BL} = 0$) approximation is adopted. Eq. 9 can be directly derived from eq. 5. We call this method 2, given as

$$S_{11} = \Gamma_{AL} \tag{7}$$

$$S_{22} = \frac{\Gamma_{BS}(\Gamma_{AL}-\Gamma_{AO})+\Gamma_{BO}(\Gamma_{AS}-\Gamma_{AL})}{\Gamma_{BO}\Gamma_{BS}(\Gamma_{AS}-\Gamma_{AO})} \tag{8}$$

$$S_{12}S_{21} = \frac{(\Gamma_{BS}-\Gamma_{BO})(\Gamma_{AS}-\Gamma_{AL})(\Gamma_{AO}-\Gamma_{AL})}{\Gamma_{BO}\Gamma_{BS}(\Gamma_{AS}-\Gamma_{AO})} \tag{9}$$

Both methods 1 and 2 consider part of the calibration circuit to be idealized. Thus, the results cannot be accurate. We do not use any approximation, and derive the complete eq.7 - 9, call this method 3, given as

$$S_{11} = (\Gamma_{AL}\Gamma_{AO}\Gamma_{BL}\Gamma_{BS} - \Gamma_{AL}\Gamma_{AS}\Gamma_{BL}\Gamma_{BO} - \Gamma_{AL}\Gamma_{AO}\Gamma_{BO}\Gamma_{BS} + \Gamma_{AL}\Gamma_{AS}\Gamma_{BO}\Gamma_{BS})/k \tag{10}$$

$$S_{22} = (\Gamma_{AL}\Gamma_{BO} - \Gamma_{AO}\Gamma_{BL} - \Gamma_{AL}\Gamma_{BS} + \Gamma_{AS}\Gamma_{BL} + \Gamma_{AO}\Gamma_{BS} - \Gamma_{AS}\Gamma_{BO})/k \tag{11}$$

$$S_{12}S_{21} = (\Gamma_{AL} - \Gamma_{AO})(\Gamma_{AL} - \Gamma_{AS})(\Gamma_{AO} - \Gamma_{AS})(\Gamma_{BL} - \Gamma_{BO})(\Gamma_{BL} - \Gamma_{BS})(\Gamma_{BO} - \Gamma_{BS})/(k)^2 \tag{12}$$

$$k = (\Gamma_{AL}\Gamma_{BL}\Gamma_{BO} - \Gamma_{AO}\Gamma_{BL}\Gamma_{BO} - \Gamma_{AL}\Gamma_{BL}\Gamma_{BS} + \Gamma_{AO}\Gamma_{BO}\Gamma_{BS} + \Gamma_{AS}\Gamma_{BL}\Gamma_{BS} - \Gamma_{AS}\Gamma_{BO}\Gamma_{BS}) \quad . \tag{13}$$

From the formulas of the three methods, all methods cannot calculate $S_{21}$ and $S_{12}$ separately, only $S_{21}$and $S_{12}$ can be calculated. The microwave probe is a reciprocal device, its $S_{21}$=$S_{12}$. There is a problem of the positive and negative of $\pm\sqrt{S_{21}S_{12}}$. We propose two conditions to determine the unique phase value:

1. The phase is 0° when the frequency is 0.
2. The phases monotonically decrease as the frequency increases.

*Experiment:* The vector network analyzer used in the experiment is Anritsu MS46122B. The coaxial calibration kit is Anritsu TOSLKF50A-40. The microwave probe is Air coplanar waveguide probe (ACP). Commercial On-wafer calibration kit is used. The ambient temperature is 25℃, and the purification grade is 10,000. The calibration parameters are given by the manufacturer showing in Table 1.

*Table 1 calibration parameters of probe.*

| type | pitch | Calibration parameter | | |
|---|---|---|---|---|
| / | / | C-Open | L-Short | L-Term |
| GSG | 300μm | -14.7pF | 13.4pH | -23pH |
| GSG | 150μm | 3.5pF | -9.7pH | 4.8 pH |
| GS | 150μm | -11 pF | 49.8 pH | 57.8 pH |

In the next step, 6 reflection parameters are brought into eq.4-6, eq.7-9 and eq.10-13 to compare the difference of microwave probe *S* parameters obtained by the three methods.

We test 6 reflection coefficients and calculate the *S*-parameters of the same probe by using the above 3 methods.

Since the formula of methods 1 and 2 is $S_{11} = \Gamma_{AL}$, the results in Fig. 2 obtained by the two methods are exactly the same. The comparison shows that the data of method 2 and method 3 almost coincide completely in the low frequency band (less than 5GHz), and the difference between the two curves gradually increases with the frequency. The maximum magnitude difference of $S_{11}$ is 0.1dB. The phase error is also relatively small, with only a noticeable difference above 30GHz according to Fig 2(b).

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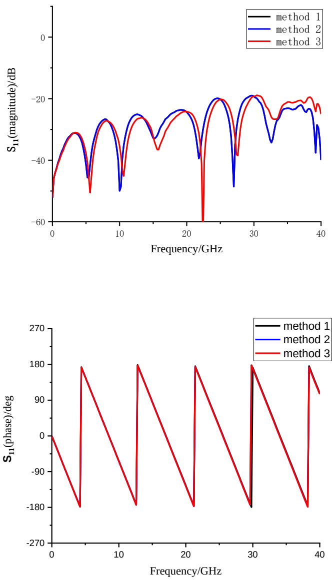


*Fig 2 $S_{11}$ Magnitude and phase calculated by the three methods,*

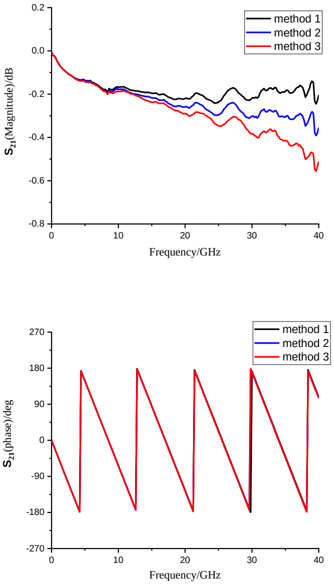


*Fig. 3 $S_{21}$ Magnitude and phase calculated by the three methods,*

According to Fig. 3, there are obvious differences among those three methods. When the frequency is greater than 15GHz, those three curves have separation, e.g., the insertion loss $S_{21}$ of method 2 is 0.15dB smaller than that of method 3. As shown in Fig. 3(b), the $S_{21}$ phase is almost coincidence, the S21 phase difference between Method 1 and Method 3 increases almost linearly with frequency, with a maximum of 3° at 40GHz.The phase difference between Method 2 and Method 1 is about 0.5° .

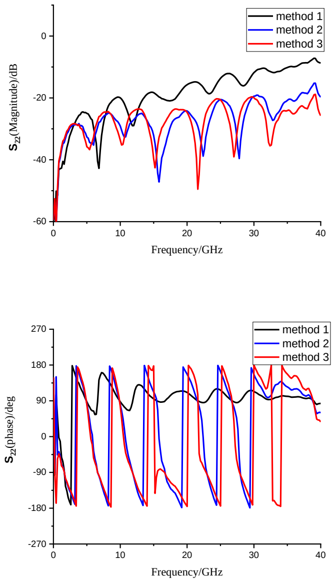


*Fig. 4 $S_{22}$ Magnitude and phase calculated by the three methods,*

Finally, the Magnitude value and phase value of $S_{22}$ are compared, as shown in Fig. 10. The maximum Magnitude of $S_{22}$ with method 1 is about -10dB, which with method 2 is -16.5dB, and which with method 3 is -19dB. The difference is obvious. Method 1 has significant errors, and the phase value is always about 90° when the frequency is higher than 5GHz, and the $S_{22}$ phase errors of method 2 is also large, and the maximum deviation of the same frequency point can reach 85° .

We also test several different types of ACP probes, and the parameters of the calibration kit corresponding to the probes are shown in Table 1. The calibration parameters of the GSG (ground-signal-ground)-150 probe is smaller. However, the calibration parameters of the GS (ground-signal)-150 probe are an order of magnitude larger GSG-150 probe calibration parameters.

For GSG-150 probe, S-parameter is compared in the Table 3, The $S_{22}$ Magnitude of method 1 is still about 7dB difference compared to the method 3, while the difference between method 2 and method 3 is very small. Therefore, the open-circuit capacitance and short-circuit p inductance that can be as small as several pF and pH levels still have a significant impact, which cannot be ignored. while the load-circuit inductance of 2-3pH level has a relatively small impact.

The comparison of S parameters of the GS-150μm probe is shown in Table 4. This probe has larger calibration parameters, it can be more clearly seen that the calibration parameters have an impact on the measurement of S parameters. Compared with method 2 and method 3, the Magnitude difference of $S_{11}$ and $S_{22}$ is more than 1.2dB, the Magnitude difference of $S_{21}$ is more than 1dB, and the phase difference of $S_{21}$ is more than 3° . It is difficult to ignore the load-circuit inductance at this condition, which has a significant impact on the S-parameter measurement of the microwave probe.

*Table 3 Comparison of S parameters of the GSG-150μm probe*

| S parameters | Method 1 | Method 2 | Method 3 |
|---|---|---|---|
| S11 Magnitude | ≤-20.2dB | ≤-20.2dB | ≤-20.1dB |
| S21 Magnitude | ≥-0.39dB | ≥-0.42dB | ≥-0.43dB |
| Maximum S21 phase difference | 3.15° | 0.2° | / |
| S22 Magnitude | ≤-13.4dB | ≤-21.2dB | ≤-21.3dB |

*Table 4 Comparison of S parameters of the GS-150μm probe*

| S parameters | Method 1 | Method 2 | Method 3 |
|---|---|---|---|
| S11 Magnitude | ≤-9.83dB | ≤-9.83dB | ≤-11.05dB |
| S21 Magnitude | ≥-1.51dB | ≥-2.37dB | ≥-1.34dB |
| Maximum S21 phase difference | 1.25° | 3.64° | / |
| S22 Magnitude | ≤-5.78dB | ≤-9.22dB | ≤-10.05dB |

*Conclusion:* We proposed a method based on SOLT calibration that fully considers the calibration parameters and exploited it to extract the S-parameters of the microwave probe. In comparison with two other incomplete S-parameter extraction methods, it was found that the size of the open-circuit capacitance and short-circuit inductance have obvious influence on the S-parameter results. The effect of load-circuit inductance was relatively small, and it is only noticeable when it is around 50pH.

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