EMPIR – 19SIP02 PlanarMeT

Introductory Guide to Making Planar S-parameter Measurements at Millimetre-wave Frequencies

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1 Introduction

Accurate characterisation of S-parameters (scattering parameters) at chip level is of great importance to the development of next generation electronic devices. The EMPIR PlanarCal Joint Research Project (14IND02) developed a Best Practice Guide (BPG) [1] for making precision planar measurements using network analysers. However, this BPG is a lengthy document and contains some complicated information that requires a high level of user expertise/knowledge. It is therefore aimed primarily at top tier measurement laboratories, such as National Metrology Institutes (NMIs), rather than more general end-users working in industry. There is therefore a need for an introductory guide (based on less complicated, practical, methods) that is a concise document aimed at the non-measurement specialist and suitable for implementation on an industrial factory floor (rather than a top-tier precision metrology laboratory).

This Introductory Guide has been developed based on the BPG and aims specifically to provide guidance to end users on implementing straightforward methods to perform reliable on-wafer calibration and measurement at millimetre-wave frequencies. High frequency on-wafer measurement is challenging and remains an active area of research. This guide will briefly review key considerations affecting the accuracy of measurement and these include experimental setup, choice of calibration methods, testing environment, crosstalk/isolation between probes, measurement verification, and design considerations for TRL calibration kits.

2 Experiment Setup

2.1 VNA

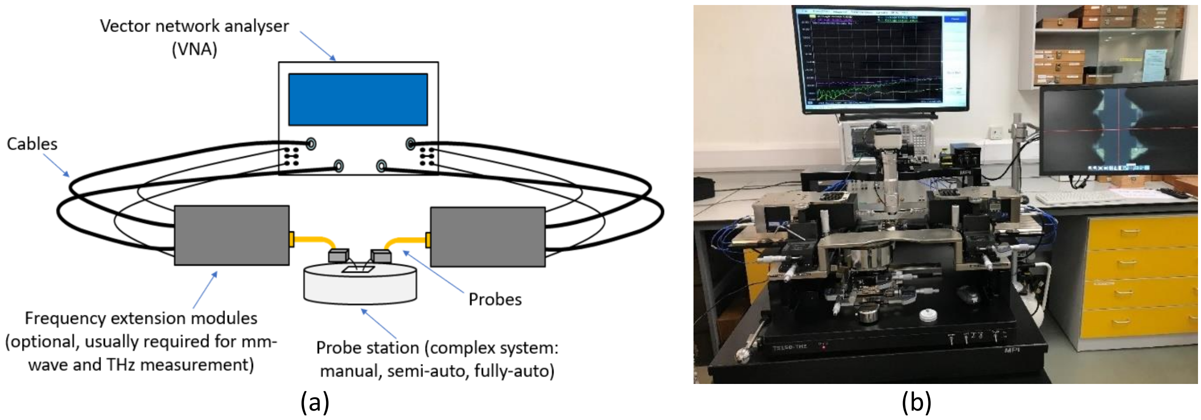


Figure 1: (a) Diagram of a typical on-wafer S-parameter measurement system. (b) Photograph of the millimetre-wave on-wafer measurement system at the National Physical Laboratory (NPL).

Planar S-parameter measurements at millimetre-wave frequencies are usually undertaken using vector network analysers (VNAs), as shown in Figure 1(a). The typical measurement setup consists of (i) a four-port VNA; (ii) two frequency extension modules; (iii) two ground-signal-ground (GSG) probes; (iv) probe station; and (v) bias supply (for measurement of amplifiers or non-linear circuits). As an example, Figure 1(b) shows the millimetre-wave S-parameter measurement setup at NPL, which is based on a manual probe station.

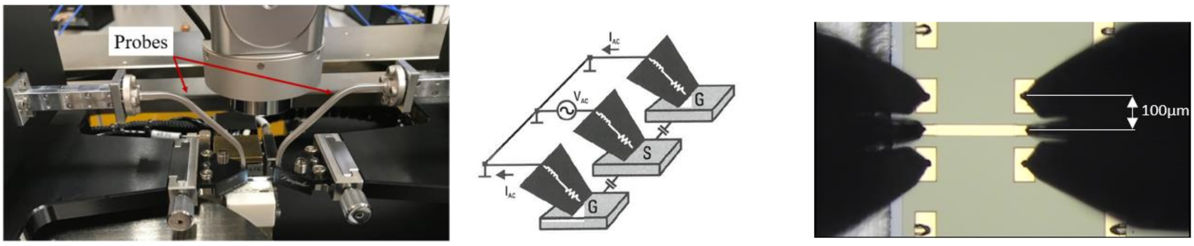
There are usually two sets of coaxial cables connecting the VNA to the frequency extension modules. These cables need to be properly connected and tightened (using torque spanners), to achieve stable measurement responses. To reduce instrumentation errors due to these cables, cable movements or bending should be minimized, particularly for cables supplying the local oscillator (LO) signal to the extension modules [2]. A study by the National Institute of Standards and Technology (NIST), USA, indicated that changes in the electrical lengths of LO cables are the most significant source of instrumentation errors, as reported in [3]. The same study also revealed that movement of the extension modules, even after the modules are moved back to their initial positions, can result in differences in the measured forward and reverse transmission phases [3]. Therefore, the handling of cables becomes even more critical, where the absolute phase is of interest.

In terms of the settings for the VNA, NPL usually uses an intermediate frequency (IF) bandwidth of no greater than 100 Hz with no averaging, when performing calibration at millimetre-wave frequencies. Smaller IF bandwidth enables better signal-to-noise ratio (and greater calibration accuracy), at the penalty of slower sweep speed. Note that the IF bandwidth can be increased after calibration.

<u>Dos and Don'ts for VNA Setups</u>

- Do: minimise cable movement at all times and support the cables so they are not just hanging in mid-air, particularly for the cables supplying the LO signal to the extension modules
- Do: use torque spanners when making coaxial connections
- Don't: bend/twist the cables between the VNA and the frequency extension modules

2.2 Probes



(a) (b) (c)

Figure 2: (a) Photo of a pair of D-band (110-170 GHz) probes at NPL. (b) Illustration showing signal excitation at coplanar GSG probe tips [4]. (c) Microscope image of the two D-band GSG probes tips with a pitch size of 100 µm.

Most microwave probes are designed to have probe tips suitable for probing of coplanar waveguide (CPW) structures. Figure 2 shows two typical CPW ground-signal-ground (GSG) probes and their tip configuration. For the probe tips, two important considerations are: (i) uniform and compliant probe contacts; and (ii) tight impedance control [5]. Before measurement, the probe tips should be inspected visually and cleaned if contaminated. Note that the probe tips are fragile and therefore difficult to clean. It is recommended to follow the cleaning procedures suggested by the manufacturer of the probe, and the recommended procedures may vary between different probe models [5]. After that, the operator should planarize the probes using a contact substrate, i.e. adjusting the positioner planarity until all tips make even contact and generate equal marks. The DC impedance of a known load standard, e.g. on an Impedance Standard Substrate (ISS), can be measured using the probe via a Bias-T (if built in). Unexpected measured values may suggest a fault in the probe or ISS (unlikely), under which scenario a further check by the probe manufacturer is recommended.

Probes of different pitch sizes can result in noticeable differences in on-wafer measurement results, at millimetre-wave frequencies. For example, in [1], measurements were carried out by PTB, Germany, on an attenuator using GGB probes with different pitch sizes (100 µm versus 150 µm), and the transmission responses showed systematic deviation at frequencies above 50 GHz. This can be attributed to the difference in probe geometries. It is expected that probes from different vendors could lead to even larger deviations in the S-parameter measurement results. Improved performance can be achieved using smaller pitch sizes and ground-signal-ground footprints [6].

Dos and Don’ts for Probes

- Do: check and planarize probes before calibration/measurement
- Do: select probes with small pitch sizes and ground-signal-ground footprints
- Do: check the (waveguide) connection between the probes and the frequency extension modules, to ensure tight/even contact, particularly if there are suspicious resonances in the measured S-parameters (e.g. when the probe is raised in the air)

3 On-wafer Measurement

3.1 Calibration methods

There are two common calibration approaches:

- Probe tip calibration using ISSs (off-wafer calibration) + de-embedding using additional on-wafer structures (*optional*)
- On-wafer calibration using standards fabricated on the same wafer as the Device Under Test (DUT)

Basic calibration standards include Open, Short, Load, and Thru, as shown in Figure 3, with each having electrical characteristics that are very different from each other, which is preferable for the calibration. These standards are however not ideal, due to parasitic capacitance or inductance, as shown in Figure 3. Such parasitic capacitance and inductance, associated with the standards, needs to be taken into account when performing a calibration at the probe tips. Probe manufacturers usually specify calibration coefficients obtained using a commercial ISS.

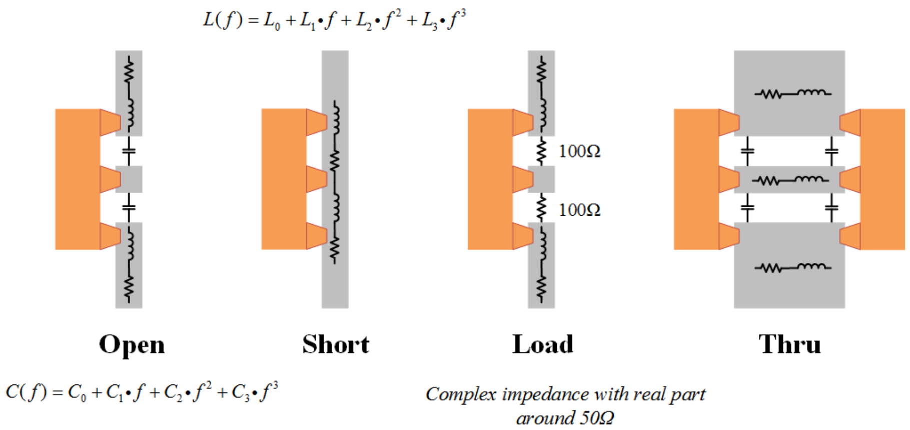


Figure 3: Typical calibration standards with parasitic capacitance and inductance [4].

Figure 4 illustrates five conventional on-wafer calibration techniques using these basic standards. These are briefly described below [4].

- SOLT requires accurate definitions of the calibration standards. SOLT is very reliable, as long as the electrical characteristics of all calibration standards are perfectly known. Calibration coefficients for standards are defined for a particular probe placement, therefore the resulting SOLT calibration is relatively sensitive to probe placement errors that are inherent in probing.
- TRL requires minimal knowledge of the electrical behaviour of the standards. The reference plane is usually set at the centre of the Thru standard. The Reflect standard can be either a Short or Open, but Reflects with the same value of reflection coefficient are required on both ports. The Line standard (with electrical phase change with respect to the Thru of around 20° to 160° at the frequencies of the measurements) provides information about the characteristic

impedance of the CPW transmission line. Each Line standard can only cover a limited frequency range, hence multiple lines are required for broadband measurements.

- Similar to TRL, the characteristic impedance of LRM is determined by the Match standard (equivalent to an infinitely long reflectionless line). The reference plane is usually set at the middle of the Line standard. The Reflect standard can be either a Short or Open, however, like TRL, it should be identical on both ports. LRM does not need knowledge about the parasitic capacitance of the Open or the parasitic inductance of the Short. However, the behaviour of the Match needs to be well understood.
- The reference plane for LRRM is usually set at the middle of the Line standard. The Reflect standard (either Open or Short) does not need to be known, however it must be identical on both ports. The Match standard can have known resistance and unknown inductance (assumed constant with frequency). The Match inductance is calculable using the Open. LRRM requires one Match standard, whereas LRM needs two. LRRM requires the same set of standards as SOLT but requires less information about the standards. This can give better results than SOLT and is less sensitive to small errors in probe placement.
- Multi-Line TRL (M-TRL), developed by NIST, has become established as a reference calibration technique. M-TRL involves multiple lines and uses all lines, to some extent, at all frequencies. Varying weighting is applied to all the Line data to resolve the problem of band breaks that can occur with conventional TRL.

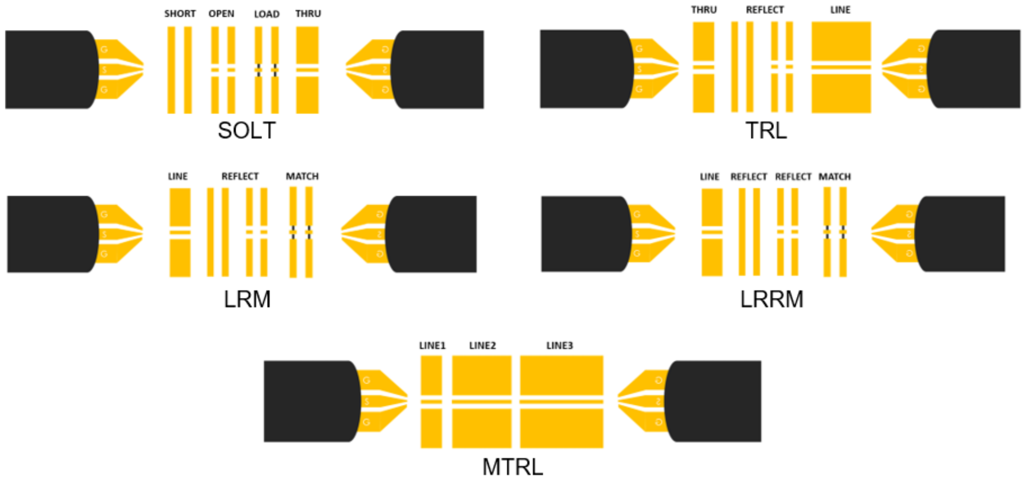


Figure 4: Diagrams of five conventional on-wafer calibration methods: SOLT (Short, Open, Load, Thru), TRL (Thru, Reflect, Line), LRM (Line, Reflect, Match), LRRM (Line, Reflect, Reflect, Match), M-TRL (TRL using multiple Lines).

The optimum calibration method depends on the exact measurement requirements. Verification standards can be used to compare different calibration methods and determine the most suitable one. Generally, TRL is a popular on-wafer calibration method, with the minimal requirement on prior knowledge of the standards and software support. It can often be difficult to obtain sufficient knowledge about the custom standards on the wafer, e.g. Load, Open, and Short, to achieve reliable calibration. TRL only needs precise information about the calibration lines and therefore is often the preferred method for high accuracy on-wafer calibration. The line dispersion that can occur at low frequencies (e.g. below 5 GHz) degrades the accuracy of TRL, making it less attractive at low frequencies unless the results are corrected for the dispersion. For off-wafer calibration, commercial ISSs contain well-known and precision standards (e.g. trimmed loads), and in theory most calibration methods work using ISSs, although in industry LRRM appears to be the more popular technique. Note that launch differences between the ISS and DUT, e.g. pad layout and/or substrate dielectric differences, can lead to additional measurement uncertainty [7]. Additional de-embedding can be adopted to address the problems associated with using off-wafer standards.

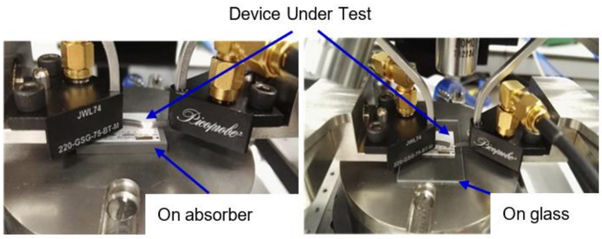
Dos and Don’ts for Calibrations

- Do: consider TRL as the preferred on-wafer calibration method
- Don’t: choose SOLT over LRRM, for off-wafer calibration, because the former demands more accurate definitions of the standards and higher probe tip positioning accuracy (i.e. more accurate and repeatable probe placement)

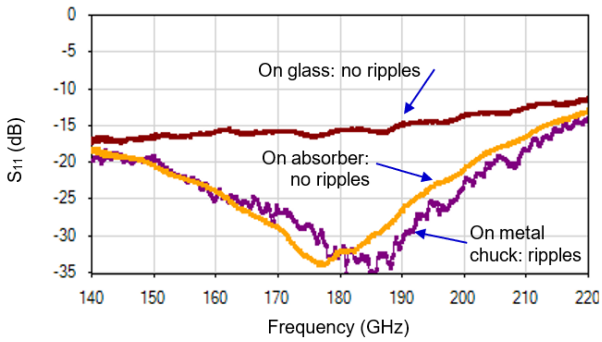
3.2 Test environment

At millimetre-wave frequencies, the test setup (e.g. the electromagnetic boundary conditions around the DUT) can have a significant impact on the measurement quality. Here, the boundary conditions mainly refer to the types of electromagnetic conditions underneath the DUT, e.g. the DUT may be placed on a metal chuck, absorber, ceramic chuck, or even suspended. More discussions on this topic can be found in [8], which reports on a detailed investigation into different boundary conditions and their impact on calibration accuracy.

Figure 5(a) shows the test setups for the same device that was placed on two different types of sample holder, one is a FormFactor absorber holder (PN 116-344) and the other is glass. Their corresponding return loss performance is shown in Figure 5(b), in which the response without sample holder under the substrate is also given for comparison. It is clear, from Figure 5(b), that the absorber holder has significantly reduced the ripples in the measured responses. These ripples are introduced by unwanted spurious modes usually excited at frequencies higher than 50 GHz [5]. If the device is placed on a metallic chuck, a small fraction of the signal can propagate as microstrip modes with the chuck acting as a ground plane. The absorber holder is capable of suppressing these modes and ultimately reducing the ripples. Note that the DUT behaves like a different structure (electromagnetically) with and without the absorber. Therefore, the boundary conditions need to be specified during measurement.



(a)



(b)

Figure 5: (a) Photographs of two different experiment setups with different boundary conditions. (b) Measured S_{11} of the DUT with different experimental setups.

The absorber effectively acts like a lossy boundary, during measurements, which has an impact on the attenuation and phase constants as well as the characteristic impedance of the CPW lines [8]. This may result in an inaccurate definition of the calibration reference impedance at high frequencies. The same study also indicated that a thick ceramic chuck yields the most accurate calibration and measurement results in terms of much reduced impact of higher-order modes and little influence on the characteristics of CPW lines. Another study [9], based on full-wave simulations, demonstrates that the optimum calibration and measurement accuracy can be achieved by using a chuck made from a material that has a dielectric constant equal to, or greater than, that of the wafer substrate.

<u>Dos and Don'ts for Test Environment</u>

- Do: use a chuck based on a material which has a similar dielectric constant as the substrate whenever possible. Alternatively, an absorbing ISS holder can be used between the metal chuck and the DUT to suppress unwanted modes.

3.3 Other high frequency parasitic effects

The accuracy of millimetre-wave on-wafer measurements depends upon many factors including the design of the CPW (see Figure 6), neighbouring structures (i.e. other components) on the calibration standards [1], etc.

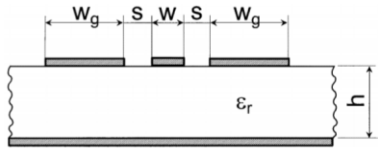


Figure 6: Diagram of a CPW. The total CPW width, W_{tot}, equals to W_g+S+W+S+W_g.

Dips may occur in the measured transmission responses of CPW, and this is attributed to radiation from the CPW and the ground plane. Full-wave simulations indicate that the total CPW width (W_{tot}) determines the frequency where the dip occurs, and the ground-to-ground spacing, *h*, influences the significance of the dip behaviour [9]. Minimizing ground-to-ground spacing is helpful in terms of eliminating the dips. To avoid the appearance of such dips, the recommended total CPW width can be calculated as follows [10]:

$$W_{tot} < \frac{2 \cdot c}{f_{max} \cdot \sqrt{2 \cdot (\varepsilon_r - 1)}}$$

where *c* is the velocity of light in free space, ε_r is the relative permittivity of the substrate, and f_{max} is the upper frequency limit.

The probe shadow region, i.e. the area below the probe that would be shadowed if the probe is illuminated from the above, should be kept free of structures. This is to avoid coupling between the probes and nearby structures surrounding the DUT or calibration standards. Otherwise, there will be noticeable dips (or resonances) in the measured transmission responses, regardless of the calibration techniques that are used. More dips could occur in the transmission responses if there are more than one neighbouring structure. This would degrade the accuracy of both measurement and calibration. This is also discussed in detail in [9].

<u>Dos and Don'ts for Minimising High Frequency Parasitic Effects</u>

- Do: follow the guidance on CPW design, when determining ground-to-ground spacing and the total CPW width
- Don't: include structures in the probe shadow region, to avoid coupling between the probe and these neighbouring structures

3.4 Crosstalk between probes

Crosstalk (or isolation) between probes can impact the accuracy of calibration and measurement at millimetre-wave frequencies. For the calibration methods mentioned above, the crosstalk should be as small as possible, ideally negligible. During calibration, there exists a small coupling or leakage between the probes, which has not been accounted for separately in the correction. The strength of the coupling varies with the distance between the two probes and the connection state of the probes (i.e. the coupling will change slightly when the probe contacts an Open, Short, Load or Line, etc). Therefore, the crosstalk is another major source of measurement uncertainty. According to the datasheet of CS-15 (the GGB calibration substrate for use above 110 GHz), crosstalk could limit the accuracy of the measurement, when the devices to be measured require probe-to-probe placement of less than 150 µm.

A 16-term error model [11] can be used for crosstalk corrections at millimetre-wave frequencies. This algorithm can correct the crosstalk effects due to the coupling between probes and the coupling between the pair of standards (e.g. Short-Short, Open-Open). This technique requires measurement of six pairs of calibration standards, i.e. Short-Short, Open-Open, Load-Load, Open-Short, Load-Open, and Load-Short, making the technique expensive to perform due to the relatively large area of wafer space being occupied. Alternatively, special probe-to-pad transitions (e.g. [12]) can be designed to reduce the crosstalk between probes and standards. Figure 7 shows an example design of a closed and shielded pad configuration for D-band [12]. It has been demonstrated that such design considerably reduces the influence on the measurements due to crosstalk, higher-order modes or neighbouring structures [12]. Either of these two crosstalk correction techniques can be adopted, when the influence of crosstalk becomes significant.

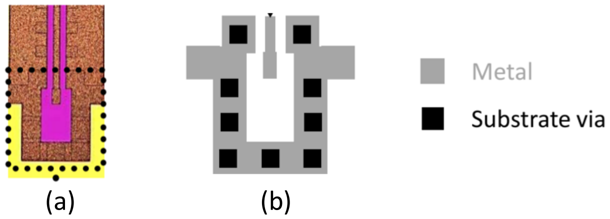


Figure 7: (a) Diagram of the design of closed and shielded pad configurations. (b) Close up view of the pad structure, represented using a black-dotted rectangle in Figure 7(a). Such design can reduce the impact of crosstalk, higher-order modes and interferences from neighbouring structures [12].

<u>Dos and Don'ts for Minimising The Effect of Cross-talk Between Probes</u>

- Do: use crosstalk correction algorithms or special pad structures to minimise the effect of coupling between probes (and between the pair of standards utilised in the calibration)

3.5 Measurement verification

It is good practice to use independent verification devices to determine/validate the quality of calibrations. These verification devices can be calculable (or modelled) devices (e.g. mismatch lines) or certified devices measured by another lab (e.g. a National Metrology Institute such as NPL, NIST or PTB). Re-measuring the calibration standards is not a good verification. Standards used for calibration are assumed to match their calibration kit definitions and will therefore appear to have good electrical performance even when their quality is not good. Therefore, calibration should be verified using other devices that were not used during calibration. In the scenario where wafer space is limited, the Open (realised by raising the probe in the air, above a bare section of the substrate) can be used as a verification standard.

It is recommended that uncorrected raw data for the calibration standards and the DUTs (including verification devices) should be obtained. This allows off-line post-processing of the DUT results by implementing different calibration methods. This approach avoids uncertainty due to multiple connections to the DUT.

Dos and Don'ts for Measurement Verification

- Do: include verification devices when designing calibration kits
- Do: consider collecting and storing the uncorrected raw data and processing the corrected results offline, during the comparison of different calibration methods
- Don't: use standards used for calibration as the verification devices

4 Design of TRL Calibration Kit

The TRL calibration kit is usually fabricated on the same wafer as the DUT. The definition of the calibration kit can be performed on most modern VNAs, which usually come with pre-programmed semi-automatic calibration routines that produce accurate calibrations with the minimum of effort. No separate software (e.g. WinCal) is required.

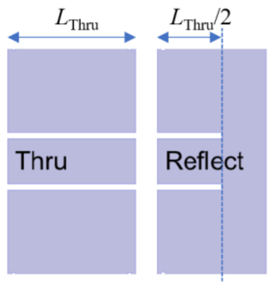


Figure 8: Diagram of the Thru and offset Short standards based on a uniform CPW structure [9].

For TRL calibration standards based on CPW structures, offset Short or offset Open devices should be utilised as the Reflect standard, with the offset being half of the Thru length, as shown in Figure 8. This is to minimize the distance between the centre of the Thru (the intrinsic calibration reference plane) and the effective Reflect, so that sign choice ambiguities in the solution of the calibration equations can be avoided [9]. When this distance is greater than λ/8 (across the entire band of interest), the sign needs to be changed to ensure phase continuity, resulting in an additional layer of complexity.

The CPW Thru and Line standards of the TRL method are effectively uniform transmission lines of different lengths. An electrical length or delay must be entered into the VNA to account for the delay in the Line standard. This length or delay should be the difference in length between the Thru and the Line, if the Thru is defined as zero length (i.e. when the calibration reference plane is defined as the centre of the Thru). Note that the delay (*T*) required by the VNA corresponds to the free space electrical length, which is greater than the physical length of line (l_{Line}) as the wave propagation speed is faster in free space than on the substrate. The corresponding free space delay can be calculated approximately using the equation below:

$$T = l_{Line} \cdot \frac{\sqrt{\frac{(\varepsilon_r + 1)}{2}}}{c}$$

where c is the speed of light and ε_r is the dielectric constant of substrate (e.g. 9.24 for alumina – i.e. dielectric material used by GGB for their calibration substrates).

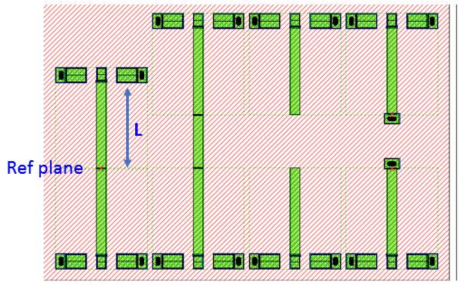


Figure 9: Diagram of the D-band TRL calibration standards fabricated on the same GaAs wafer as the devices. The calibration reference plane is at the centre of the Thru standard.

There exist millimetre-wave circuits based on microstrip lines, which can also be measured using GSG probes. In this scenario, CPW to microstrip transitions are usually required. Figure 9 shows a D-band (110-170 GHz) calibration kit which involves launches from the GSG pads to the reference plane (i.e. simple CPW to microstrip transitions) [13]. The calibration standards and verification device in [13] were fabricated on the same GaAs substrate with a thickness of 50 µm. Via holes were included to connect the upper and lower ground planes, as the ground plane of the microstrip is on the opposite side of the substrate. The length of the Thru standard (2·*L* in Figure 9) needs to be carefully designed, in order to avoid resonances in the raw measurement responses. The launches should be sufficiently long so that the microstrip mode can be fully established by the time it gets to the reference plane. Electromagnetic full wave modelling of the launch can be carried out to calculate the optimum length. On the other hand, the launch length (*L*) should be no greater than λ/8 [14], otherwise the Line standard would behave like a λ/2 resonator and bring in resonances to the transmission responses. Such resonances affect the accuracy of the calibrations.

For TRL calibration, the Reflect standard can be either a Short or Open. In [13], both Shorts and Opens have been implemented at D-band and utilised for de-embedding the raw measurement results of the verification device. As expected, there is not any noticeable difference, in [13], between the processed results using calibrations with different Reflect standards (i.e. Short and Open). This is attributed to the fact that TRL does not require perfect Open or Short standards, as long as identical values of reflection coefficient are presented at both calibration reference planes.

Dos and Don’ts for Design of TRL Calibration Kit

- Do: use offset Short or offset Open as reflect standards, with the offset being half the length of the Thru standard
- Do: leave enough distance (i.e. separation) between standards, to avoid any impact from neighbouring structures (i.e. due to electromagnetic coupling)
- Do: input the free space electrical length into the VNA when defining the calibration kit
- Don’t: make the Thru length (2·*L* in Figure 9) greater than λ/4 when simple CPW to microstrip transitions are used

5 Conclusions

This Introductory Guide has presented a summary of recommendations for carrying out on-wafer S-parameter measurements at millimetre-wave frequencies. These recommendations were developed based on the research undertaken during the EMPIR PlanarCal project (2015-2018). This Guide is expected to complement the PlanarCal Best Practice Guide, providing end-users in industry, and elsewhere, with some practical, simple to use, guidelines on achieving reliable on-wafer measurements.

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