AN SOLR CALIBRATION FOR ACCURATE MEASUREMENT OF ORTHOGONAL ON-WAFER DUTS

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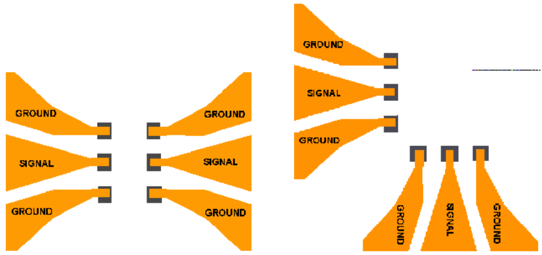
ABSTRACT

Orthogonal CPW thrus are notorious for generating undesired modes due to the bend discontinuity. These undesired modes are not accounted for in conventional calibration methods such as SOLT, LRM, and TRL, since they require, by definition, well-behaved thru standards. In this paper, we will demonstrate through experimental results how the Short-Open-Load-Reciprocal thru (SOLR) approach, which avoids imposing any dependency on the nature of the thru standard itself, provides a superior calibration.

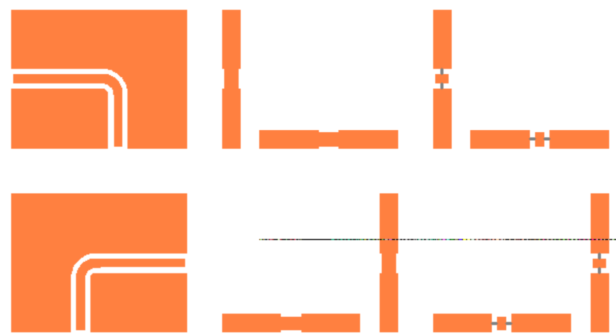
INTRODUCTION

Conventional calibration methods such as short-open-load-thru (SOLT), line-reflect-match (LRM), and thru-reflect-line (TRL) require that the thru standard be well behaved. This allows it to be modeled as a 50 Ω line with a specific loss and delay characteristic [1, 2]. This condition is relatively easy to satisfy for standard DUTs with East-West ports. The thru is typically made electrically small (about 1ps delay) so that it represents a near lossless, CPW-mode 50 Ω line. In orthogonal DUTs, however, a 'nice' CPW thru becomes difficult to fabricate (Figure 1).



(a) (b)

Figure 1. Straight across (a) and orthogonal (b) microwave wafer probing.



thru short load

Figure 2. CAD layout of the orthogonal ISS including orthogonal CPW thru standard. The 50 ohm cross-sectional impedance is maintained by the continuous bend.

The thru is not only considerably long but has a right-angle bend in it (Figure 2). The bend discontinuity, regardless of how carefully it is mitered, gives rise to a slot-line mode, and in a lesser extent to leaky parallel-plate and surface wave modes [3, 4]. We will show how these undesired modes distort the ideal CPW-mode behavior of the line and introduce a large error into a conventional calibration, but is remedied by the SOLR approach.

One approach to orthogonal probing may be to use a straight across calibration and carefully reorient the probe prior to measurement. This additional step is inconvenient and may introduce errors due to changes in electrical behavior when the cable and probe are repositioned. If this step is performed carefully using high quality phase-stable cables, however, it is possible to obtain good results.

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SOLR CALIBRATION

A variation of the SOLT calibration, the SOLR – Short-Open-Load-Reciprocal first described in [5] – does not require a known thru standard. As the name suggests the only assumption for this standard is that it is reciprocal with $S_{12} = S_{21}$ for equal impedance ports.

In the SOLT, LRM, and TRL calibrations the thru standard is defined as

$$S = \begin{bmatrix} 0 & e^{-g \cdot l} \\ e^{-g \cdot l} & 0 \end{bmatrix} \qquad (1)$$

where γ and l denote the propagation and length of the transmission line standard.

In particular, SOLT uses the thru to calculate the port match and transmission terms based on a three-measurement port system. The need for a known thru definition is eliminated in SOLR by using the switching terms of a four-measurement port system to calculate the load match error coefficients. This 8-term error model for SOLR is the same as in the TRL and LRM family of calibration algorithms [1] and is shown in Figure 3.

This error model has eight unknowns although only seven must be fully determined to complete the calibration (since S-parameters are ratios). The error box terms S_{11}, S_{22}, and $S_{12} \cdot S_{21}$ are determined from the one-port Short-Open-Load (SOL) standard measurements, essentially equivalent to the SOLT approach. Hence, in an actual one-port measurement the results for SOLT and SOLR should be identical. The relationships between the S_{12} and S_{21} terms must be determined from the reciprocal standard.

When the DUT is replaced by the reciprocal standard the measured overall S-parameters are given by the signal flow graph. The forward and reverse transmission measurements are then:

$$S_{21,m} = S_{21,a} \cdot S_{21,r} \cdot S_{21,b} \,/\, \mathrm{denom} \qquad (2a)$$

$$S_{12,m} = S_{12,a} \cdot S_{12,r} \cdot S_{12,b} \,/\, \mathrm{denom} \qquad (2b)$$

where the m, a, b, and r denote measured, error box a, error box b, and reciprocal standard, respectively. The denominator is the same for both measurements and consists of the second-order loop terms for the flow diagram and can be calculated.

The ratio of the measured transmission terms then gives an equation involving only the S_{12} and S_{21} terms of the error boxes:

$$\frac{S_{21,m}}{S_{12,m}} = \frac{S_{21,a} \cdot S_{21,b}}{S_{12,a} \cdot S_{12,b}}. \qquad (3)$$

This term, when combined with the products obtained from the two short-open-load one-port calibrations, provides enough information to complete the two-port calibration. This derivation shows that the definition of the thru is not required for the calculation of the error box terms. This characteristic of the SOLR calibration approach is powerful in probe card applications and for orthogonal DUTs. In these cases the ports may be physically distant or may require angled thru connections.

The SOLR algorithm is not available on any commercial VNA and requires external processing and software such as is available in WinCal™ [6]. While calibration is completed externally, the error coefficients are downloaded to the VNA allowing fully calibrated measurements without further intervention.

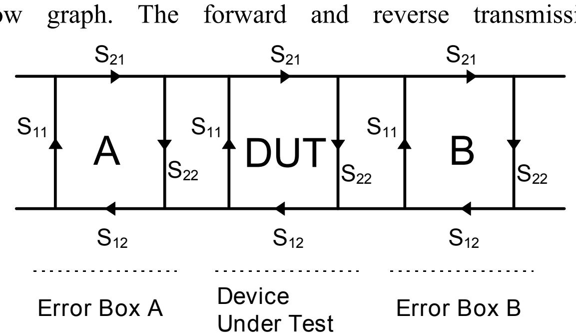

Figure 3. The signal flow diagram of the switch corrected error model.

MEASUREMENTS

A number of calibrations were made to compare the performance of the different methods. Probe placement errors were reduced by precise positioning using a Cascade Microtech Summit 10101 semi-automatic probe station. After the open, short, load, and thru measurements were made we computed (using WinCal) SOLR, SOLT, and LRRM error coefficients based on the same data. This allows direct comparison of calibration methods and avoids the distractions of minor measurement variations and noise. Each calibration was downloaded to the HP 8510 VNA using WinCal and various S-parameters were measured.

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TRL calibration was not included in this study. The sole reliance on the behavior of the thru lines for TRL calibration means it will be expected to have the worst performance for right-angle DUTs. The LRRM calibration is a variation of the LRM calibration that has been successfully validated by comparison with the NIST multi-line TRL method [7, 8].

The probe reorientation method using an LRRM calibration algorithm was used as a benchmark calibration. A calibration verification step is essential to ensure that only acceptably small changes in calibration coefficients have occurred when the probe is repositioned. After performing a straight across LRRM calibration, a measurement of the open standard (probe in air) is stored as a reference. After the probe was repositioned the open measurement was repeated and the magnitude of the vector error difference was computed. This is shown in Figure 4 and shows that the electrical behavior of the cable and probe were minimally changed.

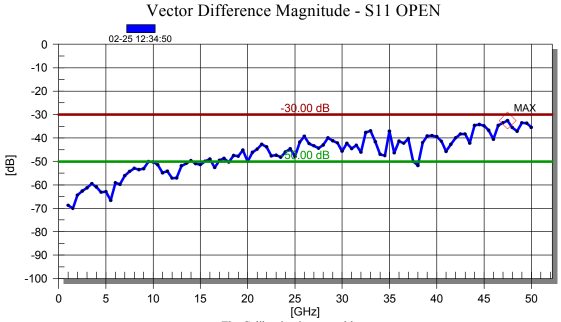

Figure 4. Calibration verification shows that the cable and probe were minimally disturbed by repositioning the probe from the straight-across to right-angle orientation.

Figure 5 shows the transmission measurements on the right-angle thru standard with different straight and orthogonal calibrations made using the Impedance Standard Substrate depicted in Figure 2. Both SOLT and LRRM orthogonal calibrations have the same zero loss characteristic since those are the defined parameters entered into the calibration. On the other hand, the orthogonal SOLR and straight-across LRRM calibrations measure the actual nature of the right-angle thru. Beyond 18 GHz the S_{21} magnitude deviates significantly from ideal behavior. The orthogonal SOLT and LRRM calibration based measurements fail to show these features.

As a further demonstration, the probe was again repositioned to the straight-across configuration and the

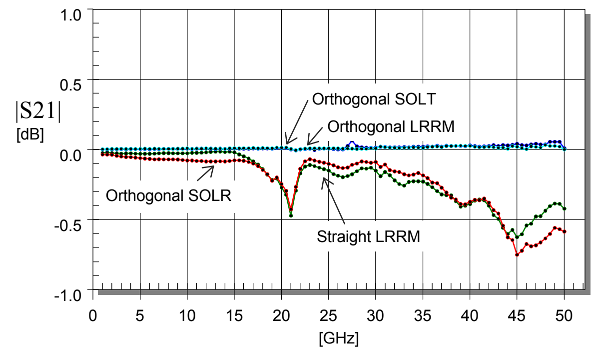

Figure 5. Insertion loss measurements of a right-angle CPW thru standard using straight-across LRRM and orthogonal LRRM, SOLT, and SOLR calibrations.

1 ps thru measured using the orthogonal calibrations. In figure 6 the proper behavior for the thru obtained after the straight-across LRRM calibration is compared to the various orthogonal calibrations. Only the SOLR orthogonal calibration provides a correct measurement of the 1 ps thru. This indicates that the non-ideal right-angle thru standard, when used with calibration algorithms that assume ideal behavior, will result in erroneous calibrations.

DISCUSSIONS AND CONCLUSIONS

The measurement results clearly show that, despite careful design of a CPW bend, the desired goal of electrical behavior with true thru line characteristics has not been achieved. It is our recommendation that orthogonal on-wafer measurements be made either with an SOLR right-angle calibration or a good straight calibration (such as LRRM, TRL or multi-line TRL) followed by careful repositioning of a probe. SOLR is clearly very convenient for right-angle measurements since it does allow elimination of the painstaking step of moving a probe without disturbing cables and avoiding any danger of incurring cable error. SOLR is also valuable for use with microwave probe cards where the probe separation is fixed and designed to match a particular die. An exactly correct thru line length may not be available even for straight paths and a general purpose line with excess length may need to be used. The SOLR algorithm gracefully ignores the loss and extra reactance introduced by the excess length stubs and provides consistently good results.

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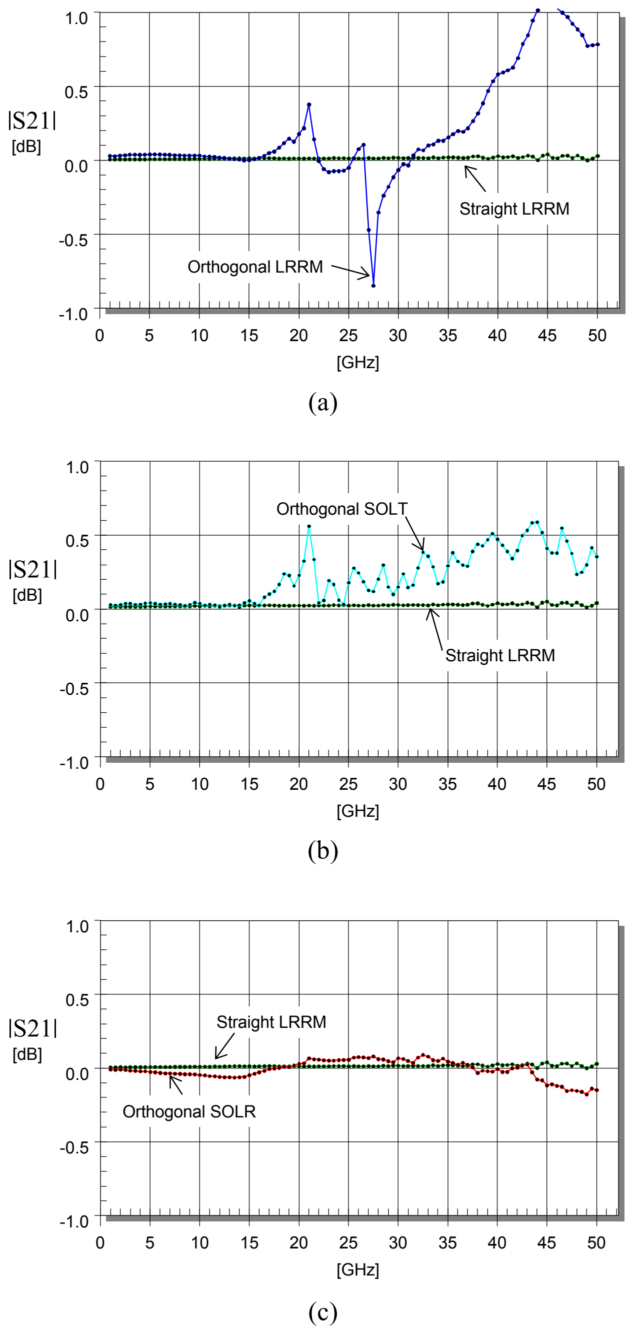

Figure 6. Insertion loss measurements of a straight lps CPW thru standard using reference straight-across LRRM and orthogonal (a)LRRM, (b)SOLT, and (c)SOLR calibrations.

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