Comparison of SOLR and TRL Calibrations

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***Abstract*- We examine a short-open-load-reciprocal scattering parameter calibration in both in-line and orthogonal probe configurations. We explore its standard definitions and verify its accuracy by comparing it to a multiline thru-reflect-line calibration.**

INTRODUCTION

We study two-port short-open-load-reciprocal (SOLR) probe-tip calibrations [1] with both in-line and orthogonal probe-head placements. We verify the accuracy of the SOLR calibration by comparing it to a multiline thru-reflect-line (TRL) calibration [2] and show that the differences are due, in large part, to the definitions of the SOLR standards.

The SOLR calibration [1], [3] makes no assumptions about the transmission standard used other than that it be reciprocal (i.e., $S_{12} = S_{21}$). A significant advantage of this permutation of the short-open-load-thru (SOLT) calibration is that it is applicable to orthogonal probing systems where the thru standard is difficult to implement: in an orthogonal probing environment, a transmission line with a 90° bend suffices for the reciprocal standard.

In this paper we compare in-line and orthogonal SOLR calibrations with accurate multiline TRL calibrations. We study the in-line case to verify the method without the additional complications of the 90° bend in the reciprocal standard of the SOLR calibration and to examine how the standard definitions effect the accuracy of the SOLR calibration. We study the orthogonal calibration separately to investigate the effects of the bend.

REFERENCE CALIBRATION

We assessed the accuracy of the SOLR calibrations by comparing them to a multiline TRL reference calibration with the method of [4]. This method determines an upper bound for $|S'_{ij} - S_{ij}|$, where S'_{ij} are the S-parameters of any passive device measured by the SOLR calibration, S_{ij} are the S-parameters measured by the TRL calibration, $|S_{11}| \leq 1$, $|S_{22}| \leq 1$, and $|S_{12} S_{21}| \leq 1$.

The TRL artifacts used for the reference calibration consisted of a coplanar waveguide (CPW) thru line 0.550 mm long, five longer lines of length 2.685 mm, 3.750 mm, 7.115 mm, 20.245 mm, and 40.550 mm; and symmetric shorts offset 0.225 mm from the beginning of the line. The CPW lines were made by evaporating a 50 nm thick adhesion layer of titanium, and then a 500 nm thick gold film, onto the 500 μm thick gallium arsenide substrate. The lines had a center conductor width of 64 μm separated from two 261.5 μm wide ground planes by 42 μm gaps. We set the reference plane of the TRL calibration 25 μm in front of the physical beginning of the TRL lines. We also measured the characteristic impedance Z_0 of the CPW lines with the method of [5] at each frequency and used Z_0 to set the calibration reference impedance to 50 Ω.

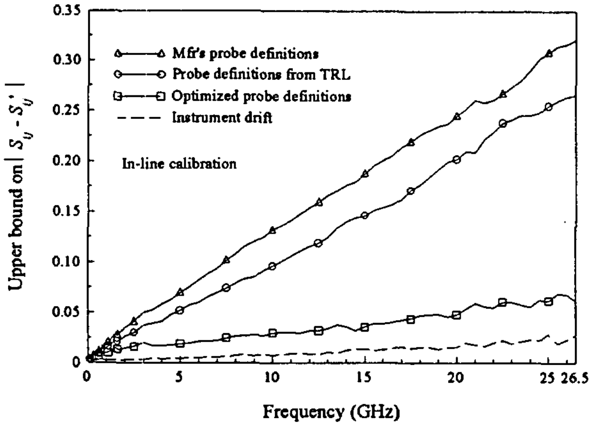

Fig. 1. Measurement error bounds for an in-line SOLR calibration. The various curves represent different SOLR standard definitions. The error bound due to test set drift and contact errors is shown as a dashed line for comparison.

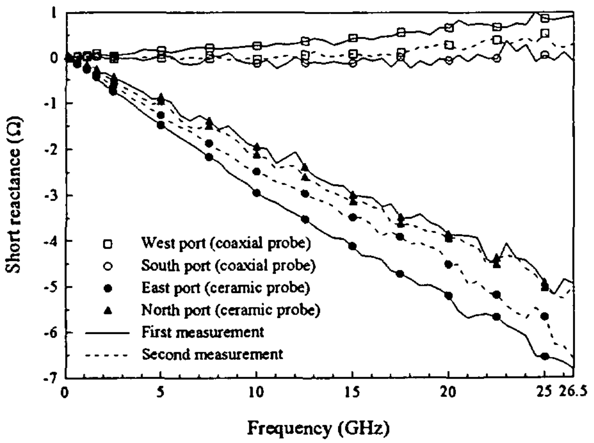

Fig. 2. Imaginary part of the SOLR short standard impedance. Repeated measurements were made with all four probe heads of the four-port test system and then corrected with a TRL calibration.

We used a commercial software package and shorts, loads, thrus, and bends fabricated on a commercial impedance standard substrate (ISS) to perform the SOLR calibrations. The short standard is realized on this ISS by placing the probes on a uniform sheet of conductive gold metal. The open standard is realized by raising the probes in the air, and the matched loads consisted of 50 μm square thin-film resistors laser-trimmed to 50 Ω connected to 50 μm wide vertical contact pads.

IN-LINE SOLR CALIBRATION

We first performed the SOLR calibration using the standard definitions supplied by the manufacturer. Table 1 lists the values of the shunt capacitance C_o of the open standard, the series inductance L_s of the short standard, and the series inductance L_t of the matched load terminations they specified, as well as others used in these experiments. These definitions depended on the probe type and probe pitch, as explained in [6], [7], [8], and [9].

Figure 1 compares our in-line TRL calibration to this SOLR calibration with the curve marked with triangles; the dashed curve shows the instrument drift determined from TRL calibrations performed at the beginning and the end of the experiment. This large error bound shows that this SOLR calibration fails to reproduce the TRL calibration accurately (i.e., within the limits imposed by instrument drift and contact errors). This may be due in part to inconsistencies between the ISS we used, which realizes the short by placing the probe on a sheet of conductive metal, and the standard definitions developed by the manufacturer for an ISS that realizes the short by contacting a narrow conducting bar.

We also measured each of the standards on the SOLR calibration substrate with each probe type and our TRL calibration. Figure 2 shows the reactance of the short calibration standard used in the SOLR calibrations as measured by the TRL calibration. The figure shows a dramatic difference in short reactance between the coaxial probes and ceramic probes we used on the station. These differences forced us to customize our standard definitions for each probe type in the experiment as well.

Substituting the standard definitions we determined from our TRL measurements into the

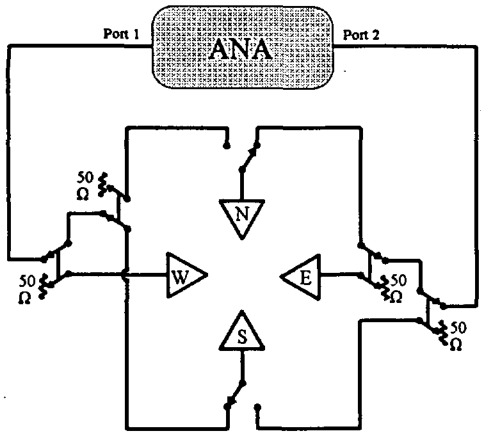

Fig. 3. Four port measurement system schematic.

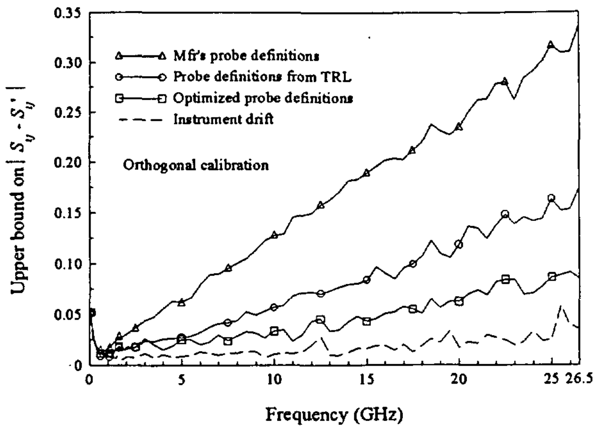

Fig. 4. Measurement error bounds for an orthogonal SOLR calibration. The various curves represent different SOLR standard definitions. The error bound due to test set drift and contact errors is shown as a dashed line for comparison.

SOLR calibration produced the error bound marked with circles in Fig. 1. While there is some improvement in the error bound, it is still considerably larger than the instrument drift, indicating additional systematic error.

Finally, we tried adjusting each of the SOLR standard definitions manually in an attempt to duplicate as closely as possible the TRL calibration. The minimum error bound we were able to achieve is marked with squares in Fig. 1. This optimization method was fairly successful, but the error bound is still well above the instrument drift. However, our measurements also showed that the real components of the impedances of the standards on the ISS varied somewhat with frequency, phenomena that could not be accounted for by adjusting C_o, L_s, and L_t. This may explain the additional error.

ORTHOGONAL SOLR CALIBRATION

We used a combination of two in-line TRL calibrations performed in the orthogonal planes of the four-port measurement system [10] of Fig. 3 to verify an orthogonal SOLR calibration. The system comprises a two-port microwave test set connected to four probe heads with a coaxial switch matrix to provide repeatable electrical connections without cable disconnection or repositioning of the probes. The west and south probes were of a coaxial construction and had a 150 µm pitch; the north and east probes were of a ceramic construction and had a 250 µm pitch.

To perform the orthogonal TRL calibration, we first set the switches so that port one of our vector network analyzer was connected to the west probe and port two to the east probe (see Fig. 3), and then performed a one-tier in-line TRL calibration between them. We then set the switches so that port one of our vector network analyzer was connected to the south probe and port two of the analyzer was connected to the north probe, and performed a second tier in-line TRL calibration between the south and north probes. This second-tier calibration determines two "error boxes," which are uniquely determined because the switching network is passive and reciprocal. The first of these error boxes translates the west measurement reference plane to the south reference plane; the second translates the east reference plane to the north reference plane. By cascading the second of these error boxes onto port two of the one-tier west-east calibration, we created our orthogonal west-north calibration.

Figure 4 compares our orthogonal TRL and SOLR calibrations. The curve marked with triangles shows the error bound using the manufacturer's standard definitions for C_o, L_s, and L_t. As in Fig. 1, the error bound is much larger than the instrument drift (dashed curve) determined from TRL calibrations performed at the beginning and end of the experiment, thus indicating large systematic errors in the SOLR calibration.

We then measured the SOLR calibration artifacts with the TRL calibration and determined C_o, L_s, and L_t from the imaginary component of each respective impedance, as we did for the in-line calibration. Again, our measurements dictated that we use different standard definitions for each probe. Using these values for the standard definitions in the SOLR calibration produced the measurement error bound marked with circles in Fig. 3.

Finally, we adjusted C_o, L_s, and L_t to minimize the SOLR calibration measurement error. The resulting error bound is shown in the curve marked with squares in Fig. 3. The measurement error bound is still above the bound for the instrument drift. Nevertheless, it is much improved and not very different from the same bound for the in-line SOLR calibration. This indicates that the imperfect bend standard is not a large source of error in the SOLR calibration.

CONCLUSIONS

The accuracy of the orthogonal and in-line SOLR calibrations we investigated were comparable: the use of a bend in the orthogonal calibration does not appear to cause significant error. However, using the standard definitions provided by the manufacturer, neither SOLR calibration reproduced the TRL calibration accurately. Although we achieved a considerable improvement in SOLR calibration by optimizing the standard definitions, that optimization relied upon an accurate reference calibration to guide the process.

Table 1. SOLR standard definitions.

	Port	C_0(fF)	L_s(pH)	L_t(pH)
Manufacturer	1	-1.0	8.8	1.6
	2	-10.5	9.6	2.1
From TRL	1	-9.1	1.3	-25.5
	2	-10.6	-41.4	-19.1
Opt. in-line cal.	1	-9.0	3.0	1.6
	2	-13.0	-31.0	2.1
Opt. orthog. cal.	1	-9.0	3.0	7.0
	2	-6.0	-41.0	-49.0

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