

# A Hybrid Probe-Tip Calibration for Multiport Vector Network Analyzers

Leonard Hayden, *Senior Member, IEEE*

Cascade Microtech, Inc., 2430 NW 206<sup>th</sup> Avenue, Beaverton, OR, 97006, USA, leonard@cmicro.com

**Abstract** — This paper details the first commercial implementation [1] of a hybrid multiport vector network analyzer (VNA) calibration method suited to a probing environment. The new calibration method implements the enhanced Line-Reflect-Reflect-Match with automatic determination of load inductance [2]-[5] for a number of straight thru paths to fully determine all directivity, reflection tracking, and source and load match terms as well as the associated transmission tracking terms. The remaining transmission tracking terms are found from the use of an unknown but reciprocal thru structure using a process similar to that of the SOLR [6]-[7] calibration algorithm. Combining the LRRM and SOLR algorithms creates a robust, hybrid calibration method that is insensitive to the normal variation in one-port standard behavior associated with normal probe-placement variability [8]-[9]. The hybrid calibration is also insensitive to the inherently non-ideal thru behavior of coplanar waveguide bends or loop-back structures [10].

**Index Terms** — Vector Network Analyzer, VNA, Calibration, Multiport, Probe, LRM, LRRM, eLRRM, SOLR.

## I. INTRODUCTION

Commercial makers of multiport vector network analyzer systems have recently introduced stand-alone systems capable of dramatically higher maximum frequencies, from a previous high of 20 GHz to the current maximum of 67 GHz [11]. These systems normally include software features to convert native single-ended measurement data to the common/differential mixed-mode representation [12] useful for the characterization of balanced circuits and devices. Commercially available systems rely on calibration to single-ended (non-modal) reference planes using a simple extrapolation of the 12-term error model traditionally used for two-port systems. The purpose of this paper is to provide calibration methods consistent with these assumptions and will specifically not address modal calibration methods [e.g., 13] or measurement systems attempting to provide pure-mode signals to potentially non-linear test devices [14]-[15].

The Line-Reflect-Reflect-Match (LRRM) vector network analyzer calibration with automatic load inductance correction [2]-[3] has been an accepted and reliable method for two-port on-wafer probing measurement for more than a decade. A version with enhancements for less commonly encountered circumstances (eLRRM) was recently reported [4]-[5]. LRRM is valued for its relative insensitivity to small errors in probe placement that are inherent in microwave probing [8]-[9]. Typical LRRM calibration compares favorably [16] with the

NIST reference multiline Thru-Reflect-Line (TRL) method [17]-[18] yet uses only simple fixed spacing standards. This is the same set as the Short-Open-Load-Thru (SOLT) method.

Commercial multiport VNA calibration algorithms primarily focus on calibration to a coaxial reference plane either through the use of an SOLT style calibration or the equivalent using electronically switched standards to create a multitude of states that have been previously characterized. Since every landing of a probe on planar impedance standards has uncertainty in the probe to standard positioning the assumption of such a probed standard as having fully known electrical behavior is likely to lead to inaccurate measurement.

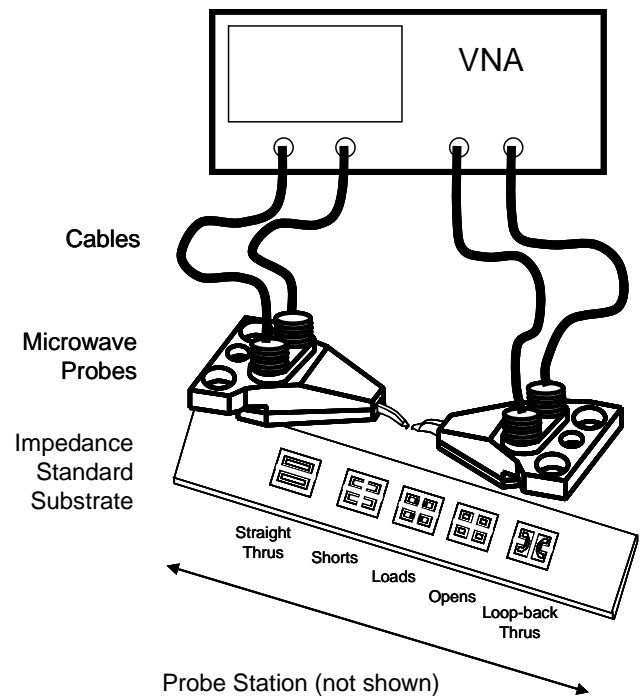


Fig. 1. A typical configuration of a four-port Vector Network Analyzer probing setup suitable for differential/mixed-mode device measurement using the hybrid LRRM-SOLR calibration method is shown. The LRRM standards are (respectively) short straight transmission lines (typically about 2 ps long), shorts, loads, and opens (in air or on substrate). The loop-back thru standards are used as reciprocal thrus in a process similar to the unknown thru step of the SOLR algorithm. Using a semi-automatic probe station to step the chuck holding the substrate allows a highly-repeatable, one-button, automated calibration.

As yet, commercial multiport systems have not yet

incorporated calibration methods that are tolerant to probe placement variations. Stand-alone multiport VNAs are capable of receiving commands and exchanging data with external software applications (such as [1]) that can address the probing specific needs.

Section II of this paper will review a commonly used multiport VNA architecture and examine the associated extended 12-term error model. The suitability for implementation of advanced calibration methods that require a simplified and self consistent error model (similar to the 8-term error model of two-port calibration) can be a challenge and will be examined. We will see how some systems do not provide access to direct measurement of the switching terms required to perform the error model reductions and we will explore ways that we can circumvent this limitation.

In section III we examine an implementation of a hybrid calibration using an LRRM calibration for port pairs to include all ports and an SOLR style unknown thru approach for remaining transmission term determination. This set of standards and the system setup is shown in Fig. 1. The tolerance for probe-placement standard variability inherent in this approach will lead to repeatable and reproducible calibration as demonstrated in section IV. This study uses calibration comparison [16], [19]-[20] to compare sensitivity of different algorithms to small differences in standards using an approach similar to that used previously for the two-port case [8]-[9].

## II. MULTI-PORT VNA ARCHITECTURE AND ERROR MODELS

In Fig. 2, the architecture of a commercial 50 GHz VNA is shown for the case of a two-port configuration and when extended to four-ports using an external test set designed for this purpose. In the two-port configuration raw S-parameters are obtained from ratios of a measurement receiver and a reference receiver. For example, the raw S-parameters  $S_{11} = A/R_1$  and  $S_{21} = B/R_1$  when the source switch is configured for port 1 as shown. The unexcited port is terminated at the source transfer switch. The second reference receiver remains active and samples the net signal present at the termination. By forming the ratio  $R_2/B$  we can establish a measure of the reflection of the termination at the switch. (Never-mind that the B and  $R_2$  samplers are not collocated, so long as these locations are always the same any error will be handled by the calibration.) For some analyzers the ratio is formulated from two separate traces that involve  $R_1$  so as to insure that the control systems remain locked. In this case  $R_2/B = (R_2/R_1)(R_1/B) = (R_2/R_1)/S_{21}$ .

Using the switch reflection terms for each choice of excitation, the traditional two-port 12-term error model (really a 6-term model for each excitation choice) can be reduced to an 8-term error model through switch correcting all of the raw standards data to correct for the effect. The two-port error models are shown in Fig. 3. This error model reduction

process has been in use for a long time but was carefully described in [21].

In a similar fashion the multiport extended 12-term error model can be reduced to a constant multiport error box plus switching terms, as shown in Fig. 4. In the most direct parallel to the two-port case, the crosstalk terms are either separately handled or neglected and the multiport error box reduces to individual two-port error boxes at each DUT port.

### A. Reduced Path Calibration Methods

The SOLT style approach to multiport VNA calibration involves using known short, open, and load standards at each port to determine the directivity ( $E_D$ ), source match ( $E_S$ ), and reflection tracking ( $E_R$ ) terms at every port. The transmission tracking ( $E_T$ ) and load match terms ( $E_L$ ) are then obtained by connecting a known thru for each combination of excitation and receive port.

This approach requires a single thru connection for a two-port analyzer, six thru connections for four-ports, and a whopping 28 thru connections for an 8-port system. In

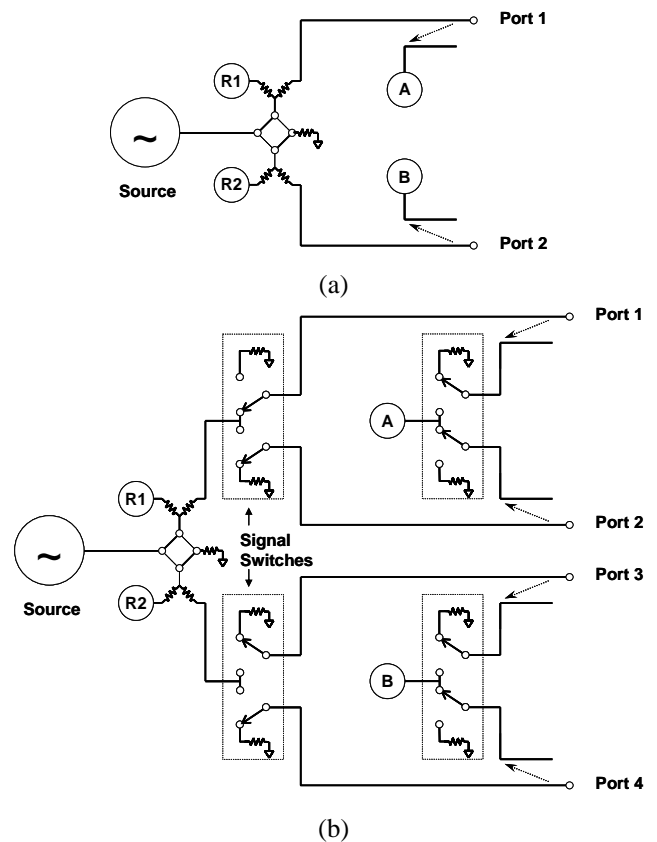


Fig. 2. Simplified VNA block diagrams of (a) 2-port PNA E8364B, and (b) 4-port PNA E8364B with N4421 test set extension.  $R_1$  and  $R_2$  are reference receivers while A and B are measurement receivers. In the 4-port configuration only the reference receiver associated with the excitation is active since the ports are terminated at the signal switch layer.

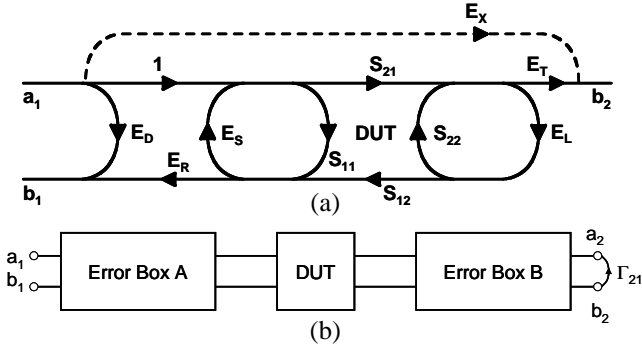


Fig. 3. Two-port VNA error models: (a) 12-term used with SOLT calibration, (b) 8-term error model used for advanced calibration methods such as TRL, LRRM, SOLR, etc. In each case the forward excitation case is shown. The reduction to the 8-term model is obtained by using knowledge of the switch termination impedances to pre-correct all of the standard measurement data used in the calibration. Crosstalk terms are either set to zero, or determined separately and handled through another data pre-correction step.

general,  $N(N-1)/2$  thru connections are required for this approach.

Calibration with a reduced number of paths often is possible. If it is known that the load match terms are independent of the choice of excitation port then it is not necessary to measure all paths. The load match terms are common and the transmission tracking terms for a connection  $i-j$  may be inferred from knowledge of the transmission tracking terms for  $i-k$  and  $j-k$  connections (completion of a triangle). For a minimal set only  $N-1$  thru connections are required although a double inference (inferring a term from an inferred term) may be required for some connection choices.

In the two probe configuration shown in Fig. 1 we have an even number of ports. Using combinations of straight thru connections and all possible loop-back connections (connections of signals to other signal paths on the same probe) allows full determination with only a single degree of inference.

**B. Multiport VNA Architecture and Switching Terms**

The multiport error models of Fig. 4 allow the impedances seen looking into the ports to be independent of the choice of the excitation port. In general, this would mean the  $E_{Lij}$  terms could differ for all choices of ports  $i$  and  $j$ , requiring all cases to be determined during calibration using the maximal combination of thru connections. In the constant multiport error box plus switching terms model this general case would imply unique values for  $\Gamma_{ij}$ .

A low frequency multiport VNA architecture that requires this flexibility has a simple tree of switches used to select the excitation port. This case would be modeled by the multiport block diagram in Fig. 2 if the source selection transfer switches are each ganged; that is, there is always one thru connection as well as one termination. The termination of a

port could either be in the first switch seen from the port end or the switch closer to the source, depending upon what port is selected as the excitation. At least one lower frequency multiport VNA uses this architecture [22].

An alternative high frequency multiport architecture opts to always terminate the port using the first switch seen from the port end. This requires the paired switches in Fig. 2 to be independent, not ganged (the architecture of the commercial system shown). Only the excitation port passes through the signal switch, all other ports are connected to the termination. This architecture is friendly to the reduced thru connection approach since all of the load match terms are independent of the excitation port.

Unfortunately the high frequency architecture of Fig. 2 with first switch termination prevents measuring the switching terms. For the connection shown with excitation at port 1, the  $R_2$  reference receiver is isolated. Using the ratios described above for the two-port case simply results in measuring noise. One could conceive of additional reference paths for each port's termination, but no doubt this was avoided in the system of Fig. 2 due to the additional hardware (and cost) required for implementation. At lower frequency such a

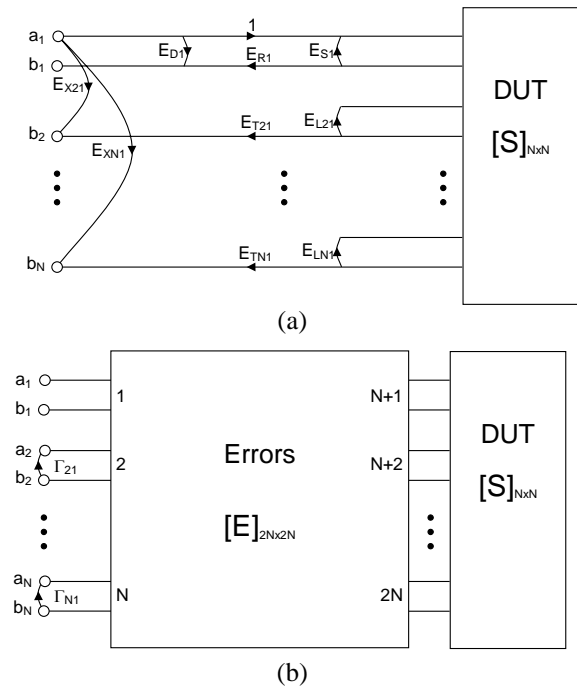


Fig. 4. Multiport VNA error models: (a) extended 12-error model ( $3N^2$  terms total), (b) extended 16-term error model used for advanced calibration ( $4N$  terms excluding crosstalk). In both cases the port one excitation is shown. The error model reduction is obtained using a straight-forward extension of the process described for two-ports by Marks [19]. Crosstalk terms are normally set to zero, if the extended 12-term style crosstalk VNA terms are included the number of non-zero terms in  $[E]$  grows by  $N(N-1)$ . When neglecting crosstalk  $[E]$  can be replaced by two-port error boxes at each port.

choice would have less cost impact and is a reasonable design trade-off.

It seems that we are at an impasse. Either we could have a costly system with source receivers on every port, a low frequency architecture where we can measure some switching terms but with a limited ability to reduce the number of thru connections, or a high frequency architecture friendly to thru connection reduction but where the switching terms needed for advanced calibration can't be measured. What can we do?

C. Indirect Acquisition of Switching Terms

This circumstance is not entirely new. One commercial implementation of TRL for a low-cost two-port network analyzer with only a single reference receiver incapable of directly measuring switching terms simply treated the switch termination as ideal, introducing considerable error [23]. A better process was described in [24] allowing accurate advanced calibration (multi-line TRL in the cited case). The single reference receiver architecture would be similar to the two-port configuration of Fig. 2 but with only one reference receiver located on the source side of the transfer switch.

Originally the published method was to use a two-tier approach. The first tier was an accurate coaxial calibration that provided the error model reduction allowing the advanced calibration in the second tier. Marks [21] provided a method to extract the switching terms ( $\Gamma_{ij}$ ) mathematically from a known good calibration and demonstrated their use in the switch correction process. This process is easily applied to the multipoint case using equations (1) and (2) from [24] for each case of port pairs.

Our initial experiments in this area used simple mechanical coaxial calibration and adapter substitution with a two-port network analyzer. The results were not usable. Only when using a modern electronic calibration module for the coaxial calibration were we able to accurately extract the switching terms. We also confirmed the statement in [24] that the use of an SOLT probe-tip calibration as the source of the switching terms was also subject to error. See Figs. 5 and 6.

III. HYBRID LRRM-SOLR MULTIPORT CALIBRATION

The hybrid calibration method is implemented in a commercial software package supporting a high degree of automation in the calibration process while requiring a minimum standard set. Only five probe-able structures need to be contacted: simultaneous equal reflect (shorts), equal reflect (opens), and match terminations at all ports along with precision straight thru connections and unknown but reciprocal loop-back thru connections, as shown in Fig. 1. The straight Thru standards are kept electrically short and the reflect and match standards are situated near the probe tips, approximately co-located with the desired measurement reference planes. This configuration is a design choice made to minimize impacts from non-ideal or unknown behavior of

the Line standard in loss, frequency dependent delay, and

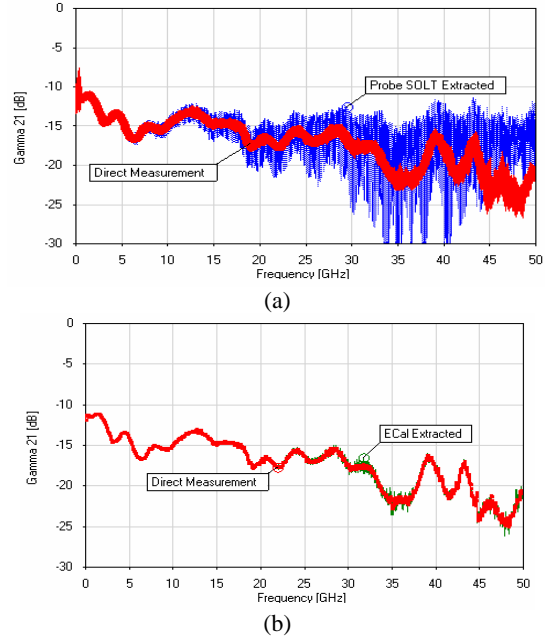


Fig. 5. Comparison of two-port switching term  $\Gamma_{21}$  extracted from calibration, compared to direct measurement: (a) probe-tip SOLT calibration, (b) coaxial calibration using electronic calibration module. The probe-tip SOLT derived  $\Gamma_{21}$  deviation is excessive and not likely to enable useful advanced calibration.



Fig. 6. Comparison of long-line measurement using different calibrations: (a) probe-tip SOLT calibration, eLRRM using switching terms extracted from SOLT, and standard eLRRM, (b) eLRRM using switching terms extracted from coaxial calibration using an electronic calibration module and measured eLRRM. The line measurement based on SOLT and SOLT derived calibrations show severe aberrations. The E-Cal derived eLRRM calibration is virtually indistinguishable from the eLRRM with measured switching terms.

impedance mismatch. It also facilitates automation of the calibration since only substrate moves are needed (no probe repositioning). This provides a convenient one-button calibration with enhanced repeatability, as in Figs. 1-2 of [8].

Each straight-thru is switch-term corrected and applied to the LRRM algorithm with the associated opens, shorts, and loads. The algorithm returns the directivity, reflection tracking, source match, load match, and transmission tracking for the associated port pair. Including every port in at least one of these port pair combinations for LRRM provides information equivalent to doing SOL on every port except much more accurately since the requirement of known one-port standard behavior is eliminated. Since the high frequency VNA system architecture provides constant load match we have knowledge of the load match at any port for any excitation. Using loop-back connections as an unknown-but-reciprocal thru connection then allows determination of the transmission tracking for the loop-back connected port pair. Finally, the remaining transmission tracking terms are inferred from these already measured terms through the triangle completion process. Crosstalk terms are either handled separately or simply set to zero (usually the best choice since the extended 12-term error model cannot accurately represent the DUT dependent crosstalk present in most fixtures).

In a four-port system, for example, the straight thru connecting ports 1 and 3 along with the one-port standards allows LRRM determination of  $E_{D1}$ ,  $E_{D3}$ ,  $E_{R1}$ ,  $E_{R3}$ ,  $E_{S1}$ ,  $E_{S3}$ ,  $E_{L31}$ ,  $E_{L13}$ ,  $E_{T31}$  and  $E_{T13}$ . Similarly the straight thru connecting ports 2 and 4 allows LRRM determination of  $E_{D2}$ ,  $E_{D4}$ ,  $E_{R2}$ ,  $E_{R4}$ ,  $E_{S2}$ ,  $E_{S4}$ ,  $E_{L42}$ ,  $E_{L24}$ ,  $E_{T42}$  and  $E_{T24}$ . Using the source port independent load match assumption  $E_{L21}$  and  $E_{L23}$  are set equal to  $E_{L24}$ . Similarly we set  $E_{L12}$  and  $E_{L14}$  equal to  $E_{L13}$ ,  $E_{L32}$  and  $E_{L34}$  equal to  $E_{L31}$ , and  $E_{L41}$  and  $E_{L43}$  equal to  $E_{L42}$ . A loop-back thru connection of ports 1 and 2 allows SOLR style determination of the transmission tracking terms  $E_{T21}$  and  $E_{T12}$ . The loop-back connection of ports 3 and 4 allows determination of  $E_{T43}$  and  $E_{T34}$ . The remaining transmission tracking terms  $E_{T41}$ ,  $E_{T14}$ ,  $E_{T32}$ , and  $E_{T23}$  are determined through the triangle completion computation using appropriate common transmission terms. Setting the  $E_{Xij}$  terms to zero then completes determination of all 48 terms of the four-port, extended 12-term error model.

#### IV. HYBRID CAL MEASUREMENT RESULTS

The performance of the four-port hybrid calibration implementation was evaluated several ways. Initial algorithm software development was debugged via a closed loop process. A representative four-port, extended 12-term error model was captured and used as part of a virtual VNA simulator. The virtual VNA has the ability to apply errors to a calibration-model defined standard behavior computing a virtual 'raw' measurement for each standard. We used this

virtual raw data as the input to the hybrid algorithm, computed the error terms, and closed the loop by comparing the computed errors to the reference set used in the virtual VNA simulator.

Optionally, the virtual VNA can include additive noise and error term drift as part of the simulation. Their inclusion allows testing the algorithm for numerical sensitivity and helps to demonstrate the robustness of the algorithm. The representative errors used in the simulator are a close approximation to an actual system's errors making this process very effective in predicting calibration algorithm performance.

Calibration sensitivity to probe placement variability was also investigated with real data. The measurement system consisted of a Cascade Microtech S300 probe station, high performance phase stable cables, Infinity i50-D-GSGSG-150 dual probes, and a 126-102 GSGSG dual probe impedance standard substrate (ISS). The ISS was mounted on the probe station's auxiliary stage which has a surface made of microwave absorbing material. The network analyzer was the Agilent 50 GHz E8364B PNA with the N4421 test set providing four-port measurement capability.

WinCal XE software [1] was used to control the system, compute calibration and calibration comparisons, and acquire and manipulate measurement data. Automated stage moves were used to maximize system repeatability. An Agilent N4692A electronic calibration module was used to provide a precision coaxial calibration supplying the switching terms.

For the test cases we used normal probe placement on the alignment marks and a position approximately 15  $\mu\text{m}$  back from the target position, see Fig. 7. For the normal probe position test case all standard data were acquired with automated stage moves. The load standard was then remeasured using the offset probe position. For each positional case both a hybrid calibration and a four-thru four-port SOLT calibration were calculated. The hybrid calibration used switching terms derived from the coaxial calibration obtained with the electronic calibration module.

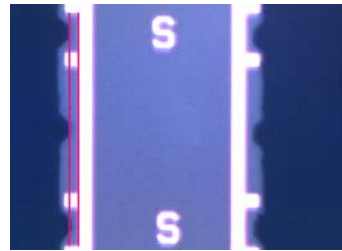


Fig. 7. The deliberate misalignment of probes for purposes of evaluating probe placement sensitivity is shown. The offset is approximately 15  $\mu\text{m}$ .

The WinCal XE calibration comparison [19]-[20] function was used to calculate the error bounds for a worst-case passive device associated with the difference in two calibrations. By comparing the results for positional offset and

the nominal position for each calibration type we gain a measure of the sensitivity of the calibration to the positional variation of the probe. The hybrid calibration shows less sensitivity to longitudinal probe positional error on the load standard than SOLT, see Fig. 8.

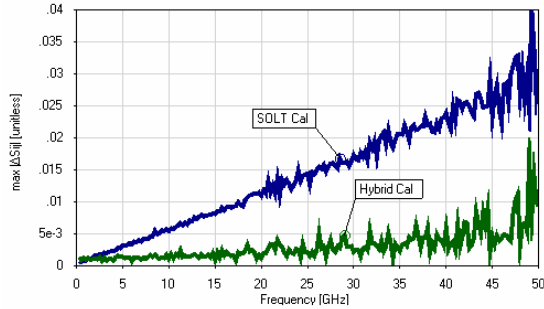
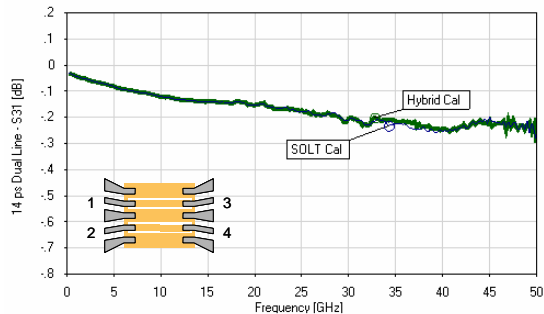
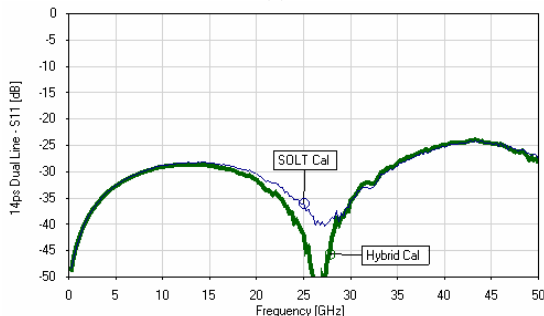


Fig. 8. The sensitivity to small longitudinal offsets in probe position on the load standard for the SOLT and hybrid calibration methods is shown. These curves bound the maximum vector error difference on a worst case passive device measurement associated with the different calibration. SOLT shows more than four times the sensitivity to longitudinal load offset than the hybrid cal.

While mathematically pleasing to use calibration comparison, it is often useful to compare practical device measurement data. Calibration comparison results tend to be dominated by small delay offsets since the theoretical worst case passive device has both unity reflection and transmission in all paths. A measurement of a well matched device reveals other details.



(a)

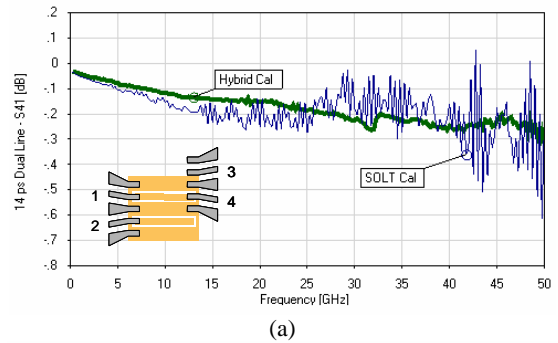


(b)

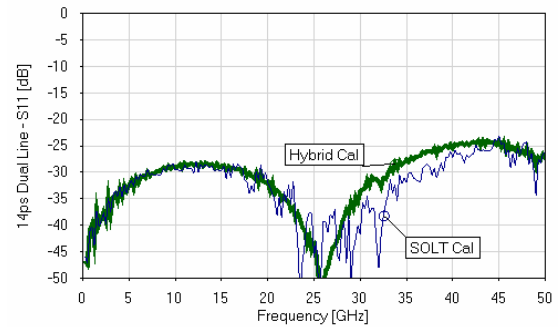
Fig. 9. SOLT and hybrid calibration measurement data of a 14 ps dual verification line for transmission magnitude (a), and reflection magnitude (b) are shown. Differences are relatively small.

The dual, parallel transmission line approximately 14 ps long available on the 126-102 ISS will serve as a useful test device. When measured in the same manner that the ports were calibrated the results are very reasonable. Fig. 9 shows that insertion loss and return loss are essentially equal for all of the test cases.

But when the measurement is made with different ports things get interesting. The right probe (with ports 3 and 4) is shifted such that the line that was connecting ports 1 and 3 instead connects ports 1 and 4. In Fig. 10 we see that the hybrid calibrations provide a consistent measurement virtually identical to the common result obtained with the port 1 and 3 measurement. The SOLT calibration is failing and shows significant error in both insertion loss and return loss.



(a)



(b)

Fig. 10. The port reconfiguration measurement data for the 14 ps line used in Fig. 9 transmission (a), and reflection (b) for the hybrid and SOLT calibration cases are shown. While the hybrid calibration result is very consistent with the common result shown in Fig. 9, the SOLT based measurement data exhibit significant error.

As a final validation of the quality of the measurement it is useful to look at the mixed-mode scattering parameter conversion. The differential S-parameters of the dual single-ended, 14 ps transmission line from the 126-102 ISS are shown in Fig. 11. Insertion loss is reduced somewhat over the single-line measurement since the loss due to coupling is not present in the differential signal case, see Fig. 12.

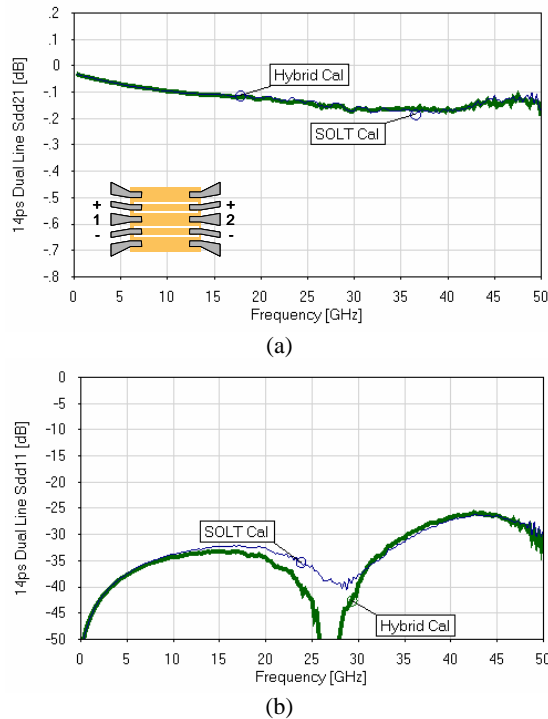


Fig. 11. The differential S-parameters obtained by mixed-mode conversion of the four-port single-ended measurement of the 14 ps, dual line on the 126-102 for transmission (a), and reflection (b) for the test cases are shown. All results are similar for this test structure. The differential insertion loss is less than the single-ended insertion loss of Fig. 9 possibly due to uncorrectable far-end crosstalk.

## V. CONCLUSION

This paper has provided a first look at a hybrid calibration that merges the strengths of the eLRRM and SOLR calibration algorithms to provide a superior multipoint calibration. Preliminary results demonstrate that the algorithm is functioning properly and that the use of a good quality coaxial reference calibration to supply switching terms works well.

The hybrid calibration is most effective with higher frequency multipoint VNA systems and in those circumstances where a thoroughly optimized and characterized loop-back thru standard is not available.

Crosstalk remains a challenge for multipoint measurement and is likely to be a dominant source of error after SOLT limitations are eliminated by using the hybrid calibration. The extended 12-term error model used in commercial VNA systems does not provide a way to correct for this effect.

## ACKNOWLEDGMENT

The author would like to thank the WinCal development team for their wonderful ability to turn seemingly strange ideas into wonderful tools for calibration and measurement.

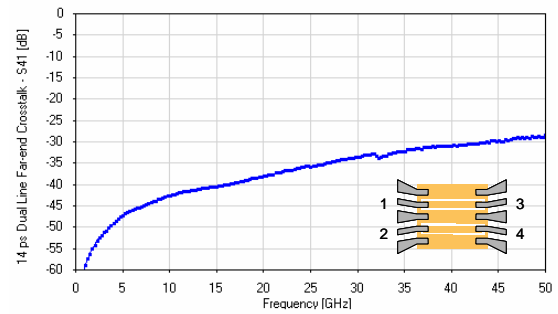


Fig. 12. Far-end crosstalk of the 14 ps dual line measured in Figs. 9 and 11. The crosstalk magnitude is independent of the length of the dual line measured and is not consistent with expected behavior of the nearly uncoupled lines. Energy on the finite-width grounds appears to be present and terminated by the parasitic ground admittance of the dual line structure and probes causing a fixture dependent effect.

## REFERENCES

- [1] *WinCal XE*, Cascade Microtech Inc., Beaverton, OR. (Available Fall 2006)
- [2] A. Davidson, K. Jones, and E. Strid, "LRM and LRRM calibrations with automatic determination of load inductance," *36<sup>th</sup> ARFTG Conf. Dig.*, Monterey, CA, Fall 1990, pp. 57-63.
- [3] E.W. Strid and A.C. Davidson, "Verification and correction method for an error model for a measurement network," U.S. Patent 5,047,725, Sept. 10, 1991.
- [4] L. Hayden, "An enhanced Line-Reflect-Reflect-Match calibration," *67<sup>th</sup> ARFTG Conf. Dig.*, San Francisco, CA, Spring 2006, pp. 143-149.
- [5] eLRRM, Patent Pending.
- [6] S. Basu and L. Hayden, "An SOLR calibration for accurate measurement of orthogonal on-wafer DUTs," *1997 IEEE MTT-S Int'l. Microwave Sym. Dig.*, Denver, CO, June 1997, vol.3, pp.1335-1338.
- [7] A. Ferrero and U. Pisani, "Two-port network analyzer calibration using an unknown 'thru'," *IEEE Microwave and Guided Wave Letters*, Dec. 1992, vol. 2, no. 12, pp. 505-507.
- [8] A.M.E. Safwat and L. Hayden, "Sensitivity analysis of calibration standards for SOLT and LRRM," *58<sup>th</sup> ARFTG Conf. Dig.*, San Diego, CA, Fall 2001.
- [9] A.M.E. Safwat and L. Hayden, "Sensitivity analysis of calibration standards for fixed probe spacing on-wafer calibration techniques," *2002 IEEE MTT-S Int'l. Microwave Sym. Dig.*, vol.3, pp.2257-2260.
- [10] R. Senguttuvan, L. Hayden, and A. Weisshaar, "Mode coupling in coplanar waveguide bends: a simple four-port model," *33<sup>rd</sup> European Microwave Conference*, Munich, Oct. 2003, vol. 2, pp. 643-646.
- [11] "Agilent test solutions for multipoint and balanced devices," Agilent Technologies, Inc. March, 2006.
- [12] W. Eisenstadt, B. Stengel, and B. Thompson, *Microwave Differential Circuit Design Using Mixed-Mode S-Parameters*, Boston: Artech House, 2006, ch. 2.
- [13] C. Seguinot, *et al.*, "Multimode TRL – a new concept in microwave measurements: theory and experimental verification," *IEEE Trans. MTT*, May 1998, Vol. 46, no. 5, pp. 536-542.

- [14] D.E. Bockelman and W.R. Eisenstadt, "Calibration and verification of the pure-mode vector network analyzer," *IEEE Trans.MTT*, July 1998, vol. 46, no. 7, pp. 1009-1012.
- [15] T. Zwick and U.R. Pfeiffer, "Pure-mode network analyzer concept for on-wafer measurements of differential circuits at millimeter-wave frequencies," *IEEE Trans. MTT*, March 2005, vol. 53, no. 3, pp. 934-937.
- [16] D. Williams, R.B. Marks, and A. Davidson, "Comparisons of on-wafer calibrations," *38<sup>th</sup> ARFTG Conf. Dig.*, San Diego, CA, Fall 1991, pp. 68-81.
- [17] R.B. Marks, "Multi-line calibrations for MMIC measurement," *36<sup>th</sup> ARFTG Conf. Dig.*, Monterey, CA, Fall 1990, pp. 47-56.
- [18] D.C. DeGroot, J.A. Jargon, and R.B. Marks, "Multiline TRL revealed," *60<sup>th</sup> ARFTG Conf. Dig.*, Washington, D.C., Fall 2002, pp. 131- 155.
- [19] R.B. Marks, J.A. Jargon, and J.R. Juroshek, "Calibration comparison method for vector network analyzers," *48<sup>th</sup> ARFTG Conf. Dig.*, Clearwater, FL, Fall 1996, pp. 38-45.
- [20] L. Hayden, "A generalized VNA calibration comparison approach," unpublished.
- [21] R.B. Marks, "Formulations of the basic vector network analyzer error model including switch-terms," *50<sup>th</sup> ARFTG Conf. Dig.*, Portland, OR, Fall 1997, pp. 107-114.
- [22] For example refer to the product manuals for Agilent Technologies, ENA series vector network analyzers.
- [23] D. Zelinka and M. Shaw, "A comparative study of TOSL, TRL, and TRL\* network analyzer calibration techniques, using microstrip test fixtures," *46<sup>th</sup> ARFTG Conf. Dig.*, Scottsdale, AZ, Fall 1995, pp. 9-18.
- [24] J.A. Jargon and R.B. Marks, "Two-tier multiline TRL for calibration of low-cost network analyzers," *46<sup>th</sup> ARFTG Conf. Dig.*, Scottsdale, AZ, Fall 1995, pp. 1-8.
- [25] A.M.E. Safwat, M. Andrews, and L. Hayden, K.R. Gleason, E. Strid, "A probe technology for 110+ GHz integrated circuits with aluminum pads," *59<sup>th</sup> ARFTG Conf. Dig.*, Seattle, Spring 2002, pp. 60-66.



Cascade Microtech, Inc.  
2430 NW 206th Ave., Beaverton, Oregon 97006, USA  
Toll Free: +1-800-550-3279 Phone: +1-503-601-1000  
Europe: +44-1295-812828 China: +86-21-6340-4183  
Japan: +81-3-5478-6100 Singapore: +65-6873-7482  
Taiwan: +886-3-5722810  
Email: sales@cmicro.com <http://www.cascademicrotech.com>

Copyright © 2006 Cascade Microtech, Inc. All rights reserved.  
All trademarks are the property of their respective owners.

APP-HYBRDCAL-1206  
Data subject to change  
without notice