Calibrating On-Wafer Probes to the Probe Tips[1]

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Abstract

This paper investigates the accuracy of on-wafer scattering-parameter calibrations at the probe tips. Data show the extent to which certain probe-tip calibrations are consistent with one another and applicable to the characterization of devices or circuits fabricated on different wafers or embedded in different transmission-line media. Calibrations to the probe tips are especially well suited to lower-frequency microwave measurements. Further results demonstrate conditions under which probe-tip calibrations fail.

Introduction

In this paper we investigate the consistency of probe-tip calibrations, which often can be realized without custom standards, in well-controlled experiments. This work is an outgrowth of a method [1] which quantifies measurement errors for lumped-element calibrations such as the open-short-load-thru (OSLT), line-reflect-match (LRM) [2,3], and line-reflect-reflect-match (LRRM) [4] methods.

Many automatic network analyzer (ANA) users prefer to calibrate their instrument without custom standards. As a result, users conventionally purchase commercial standards in configurations corresponding to the transmission lines connected to their device under test. Commercial standards are available in many common coaxial and hollow metal waveguide configurations.

In the case of circuits or devices interconnected by planar transmission lines, scattering parameter (S-parameter) characterization may be achieved using wafer probes connected to the ANA. Microwave probing is conventionally used with monolithic microwave integrated circuits (MMICs), hybrid microwave circuits interconnected by planar transmission lines, and, more recently, planar interconnections found in multi-chip modules (MCMs). Calibration standards for on-wafer probes are commercially available. Unlike the case of coaxial and hollow waveguide standards, however, commercial on-wafer probe standards are not manufactured to correspond to every transmission-line configuration. Indeed, this would be impossible. Instead, commercial calibration wafers are intended to support a universal calibration that is independent of the transmission lines connected to the device under test. Clearly, the reference planes of such a calibration must not lie beyond the probe tips, for the region beyond the tips is generally different for the device under test than it is for the standards. As a result, the intent of on-wafer calibrations using noncustom standards must be to calibrate "to the probe tips."

Conventional ANA calibrations are founded upon the assumption that only a single mode exists at the calibration reference plane, both during calibration and measurement. On-wafer probe tip calibrations clearly violate this assumption due to the discontinuity at the probe/wafer contact. In many ways, on-wafer probe-tip calibrations are analogous to the calibration of an ANA with test ports in one size of coaxial line with coaxial line of another size followed by the measurement of devices embedded in yet a third size. In both cases, the calibrations may fail to properly account for the discontinuity at the connector port.

On the other hand, it is generally accepted that probe-tip calibrations are consistent to some practical degree (e.g. [5]). This may well be true if the standards and probe tips are small compared to a wavelength, so that the classical low-frequency circuit theory may apply, and the discontinuity between the probe tips and the line is small.

How, in principle, might we arrive at an accurate probe-tip calibration? An examination of a procedure in coaxial media provides some insight. If the test port were coaxial, one could begin by connecting coaxial lines to the ANA test ports and performing a thru-reflect-line (TRL) calibration [6]. This calibration accurately measures the S-parameters at reference planes in the center of the thru, the shortest line used in the calibration. If the propagation constant is known, the calibration reference planes can be moved back to the ANA test ports with a mathematical transformation; if the reference impedance of the calibration is known, it may be set to some standard value, usually 50 Ω. If the coaxial lines and the ANA test port mated perfectly (that is, with no electromagnetic discontinuity), the transformed calibration would be valid at the ANA test port. Thus one could, in principle, calibrate at a test port by selecting a transmission line which mates without discontinuity there, performing a TRL calibration, moving the reference plane back to the test port, and setting the reference impedance to some desired value.

This basic approach is applicable in an approximate sense to on-wafer calibrations as well and ought to yield as accurate a probe tip calibration as possible. Although the probes cannot mate without some discontinuity to planar transmission lines, discontinuities are minimized when the probes mate with coplanar waveguide (CPW) transmission lines. Furthermore, since the TRL calibration method can easily be performed in CPW transmission lines and the propagation constant determined accurately [7], a mathematical transformation can be applied to move the calibration reference plane back to the probe tips. Although the initial calibration reference impedance is set to the characteristic impedance of the lines [8], that impedance can be measured and the reference impedance set to 50 Ω [9,10].

While we expect this procedure to be more accurate than its alternatives, it is nevertheless only approximate. The low-frequency circuit theory may not apply near the probe tips, perhaps because the fields in the probe arm are modified by the presence of a dielectric substrate under the arm. Furthermore, the discontinuity at the probe tips may affect the calibration. This discontinuity in general depends on the intimate details of the interaction between the probe tips and the line. For instance, the overlap of the coplanar lines printed on the underside of the probe arm with those on the wafer may be critical. Each CPW standard line leads to a different calibration.

If all of these probe-tip calibrations are valid, however, they must all be identical. In this work, we perform a number of probe-tip calibrations with different CPW lines and examine their differences using the comparison technique of [1]. In each case we perform a TRL calibration in a different CPW line, move the calibration reference plane to a position just in front of the probe tips, and set the reference impedance to 50 Ω. We then compare the calibrations to determine the extent to which measurements performed with each calibration can differ. The study shows that our CPW calibrations to the probe tips are indeed interchangeable to a significant degree, particularly when the calibrations are performed on substrates with similar dielectric constants and at low frequencies. This indicates that any one of these calibrations might be applicable to a variety of measurement situations.

A calibration to the probe tips, even if valid and accurate, is not always the appropriate calibration. For instance, consider the measurement of a device embedded in microstrip, with via transitions to the probe contact pads. A measurement of such a structure at the probe tips includes not only the device but the vias as well. This may be quite different from the measurement of the device alone at reference planes in the microstrip. To quantify these differences, we compare CPW and microstrip calibrations. Our data shows that the two calibrations are not, in fact, interchangeable, even when the microstrip calibration reference impedance is set to 50 Ω and its reference plane is moved back to the vias. This indicates that a custom calibration is required for the microstrip measurement.

Comparison of CPW Probe-Tip Calibrations

The technique for comparing calibrations is based on determining two matrices (the "error boxes") relating them. Once these matrices have been determined, the worst-case deviations of the measured S-parameters S^M_{ij} measured by one calibration and the S-parameters S_{ij} measured by the second can be determined as described in [1]. Each experiment required the performance of calibrations separated in time by approximately one to two hours. Thus the differences between the calibrations are due not only to the use of different calibration artifacts, but to random connect and disconnect errors and test-set drift as well. To separate these differences, we began the experiment with an evaluation of the connect and disconnect errors and test-set drift in our experimental setup by comparing calibrations performed at different times but based on the *same* artifacts. The resultant measure ϵ, which bounds the differences $|S^M_{ij}-S_{ij}|$, are plotted in Fig. 1. The corresponding ϵ for calibrations in the following experiments can be compared to those of Fig. 1 to determine if they contain a significant systematic component due to differences in the calibrations artifacts.

Each experiment begins with a multi-line TRL calibrations [7] performed with CPW thru lines 550 μm long, five lines of additional length 2.135 mm, 3.2 mm, 6.565 mm, 19.695 mm, and 40 mm, and two shorts offset 0.225 mm from the beginning of the line. These lines were fabricated on a 500 μm thick GaAs wafer and had a center conductor of width 73 μm separated from two 250 μm ground planes by 49 μm gaps. In each calibration, the capacitance of the lines was found from the reflection coefficient and dc resistance of a small lumped load terminating the lines, as explained in [10]. The characteristic impedance Z_o of the lines was found from the capacitance and propagation constant of the lines, as explained in [9]. Following the initial calibration, we performed a second calibration with a set of artifacts which differs in some way from the initial calibration.

The physical parameters of the lines used in each experiment are summarized in Table 1. To simplify the interpretation of the data we attempted to vary significantly only one of the physical parameters of the lines used in the second calibration while keeping all of the other physical parameters constant. For example, the two sets of lines compared in the "quartz" calibration (see Table 1) have nearly identical conductor geometry, metal thickness, and composition. The two sets of lines differ primarily in that they are constructed on different dielectrics. This shifts the characteristic impedance and propagation constants of the lines, but does not modify other factors such as the overlap of the CPW lines in the probe tips and those printed on the substrate.

In Fig. 2 our probe-tip calibrations are compared. These calibrations relate the impedance-transformed S-parameters with reference impedance Z_{ref}= 50 Ω at a position 25 μm from the beginning of the lines, which corresponds very nearly to a position at the tips of the microwave probes used to contact the lines. Thus these calibrations correct for only very short sections of line between the probe tips and the calibration reference plane. Figure 2 shows that our probe-tip calibrations, while measurably different, are very nearly interchangeable at low microwave frequencies, even thought they are based on CPW lines of quite different construction. The data also indicate that the probe-tip calibrations are nearly interchangeable at higher microwave frequencies except in the cases where the center-conductor line width and substrate dielectric constant changed significantly.

Comparison of Probe-Tip and Microstrip Calibrations

We also compared microstrip calibrations based on artifacts from a test wafer fabricated for the Software Validation Project described in [11] to one of our CPW calibrations based on CPW lines with a 1.5 μm conductor thickness. The results of the comparison are labeled with hollow diamonds in Fig. 2. In this case even the probe-tip calibration, which does not account for the via transition between the probe tip and the microstrip line, would not be expected to correspond closely to the microstrip calibration at the same reference impedance and physical reference position because it does not account for the effects of the vias. This is demonstrated clearly by the data.

Conclusion

In this work we evaluated the degree to which various probe-tip calibrations differ. The results of the study indicate that, while there are measurable differences between 50 Ω probe-tip calibrations, the differences are usually small. Exceptions occur at high microwave frequencies when the conductor geometry or substrate dielectric constant of the transmission lines used in the calibration differs significantly. This indicates that a single calibration to the probe tips may be applicable to a wide variety of measurement situations. The study was by no means complete, however. Variations in the metal resistivity and ground plane width, both of which could affect the calibration, were not studied, for example. Possible interaction of the device to be tested with the probes which might invalidate the calibration also was not considered.

A comparison of a probe-tip calibration to a microstrip calibration showed significant measurement discrepancies result even when the reference plane positions and the reference impedances were both set equal. This suggests that the effects of the via transitions on the measurement, which were not accounted for by the probe-tip calibration, were large, and demonstrates at least another limitation of probe-tip calibrations.

References

1. D. F. Williams, R. B. Marks, and A. Davidson, "Comparison of on-wafer calibrations," *38th ARFTG Conf. Dig.* (San Diego, CA), Dec. 1991.

2. H. J. Eul and B. Schiek, "Thru-match-reflect: One result of a rigorous theory for de-embedding and network analyzer calibration," *Proc. 18th European Microwave Conference*, pp. 909-914, Sept. 1988.

3. J. T. Barr and M. J. Pervere, "A generalized vector network analyzer calibration technique," *34th ARFTG Conf. Dig.* (Ft. Lauderdale, FL), Dec. 1989.

4. A. Davidson, K. Jones, and E. Strid, "LRM and LRRM calibrations with automatic determination of load inductance," *36th ARFTG Conf. Dig.* (Monterey CA), Nov. 1990, pp. 57-62.

5. P. Walters, R. Pollard, J. Richardson, P. Garnard, and P. Sucher, "On-wafer measurement uncertainty for 3-terminal active millimeter-wave devices," *Proceedings of the 1992 GaAs IC Symposium*, pp. 55-58.

6. G. F. Engen and C. A. Hoer, "Thru-reflect-line: An improved technique for calibrating the six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987-993, Dec. 1979.

7. R. B. Marks, "A multi-line method of network analyzer calibration," *IEEE Trans. Microwave Theory and Tech.*, vol. 39, pp. 1205-1215, 1991.

8. R. B. Marks and D. F. Williams, "A general waveguide circuit theory," *J. Res. Natl. Inst. Stand. Technology*, vol. 97, Sept.-Oct. 1992.

9. R. B. Marks and D. F. Williams, "Characteristic impedance determination using propagation constant measurement," *IEEE Microwave and Guided Wave Letters*, Vol. 1, pp. 141-143, June 1991.

10. D. F. Williams and R. B. Marks, "Transmission line capacitance measurement," *IEEE Microwave and Guided Wave Letters*, Vol. 1, pp. 243-245, Sept. 1991.

11. R. Furlow, R. Y. Shimoda, D. F. Williams, R. B. Marks, and K. C. Gupta, "Benchmark for the validation of microwave CAD software," *38th ARFTG Conf. Dig.* (San Diego CA), Dec. 1991.

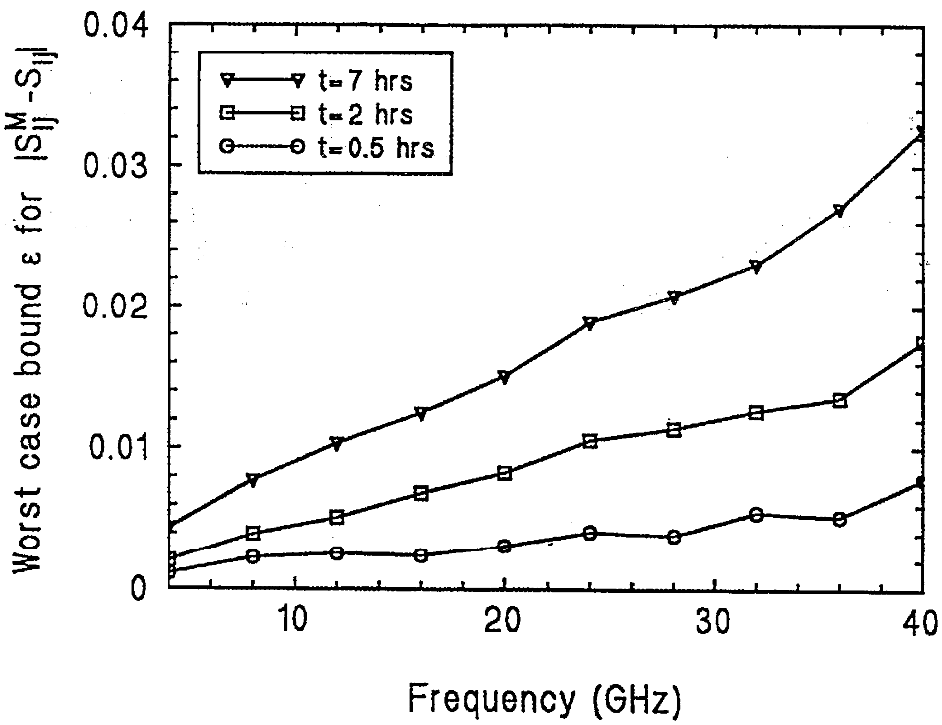

Fig. 1. The worst-case differences between calibrations performed with identical artifacts as a function of the elapsed time between calibrations. Each curve is marked by its elapsed time.

Table 1. The physical parameters of the CPW lines used in each experiment are summarized. The physical parameters of the lines used in the initial calibration are listed just below the physical parameters of the lines used in the second calibration. The physical parameters which were varied intentionally are outlined with heavy lines and printed in bold text.

Experiment	Curve Marker	Metal Thickness	Substrate Type and ϵ_r	Center cond. width	Transmission line type
Change in conductor width	●	645 nm	GaAs $\epsilon_r \sim 12.9$	**53 μm**	CPW
w=53 μm versus w=73 μm		645 nm	GaAs $\epsilon_r \sim 12.9$	**73 μm**	CPW
Change in metal thickness	▿	**222 nm**	GaAs $\epsilon_r \sim 12.9$	73 μm	CPW
t=2221 Å versus t=9762 Å		**976 nm**	GaAs $\epsilon_r \sim 12.9$	73 μm	CPW
Change in metal thickness	□	**645 nm**	GaAs $\epsilon_r \sim 12.9$	73 μm	CPW
t=6447 Å versus t=9762 Å		**976 nm**	GaAs $\epsilon_r \sim 12.9$	73 μm	CPW
Change in substrate material	○	571 nm	**Sapphire $\epsilon_r \sim 9.5$**	73 μm	CPW
Sapphire versus GaAs		568 nm	**GaAs $\epsilon_r \sim 12.9$**	73 μm	CPW
Change in substrate material	■	552 nm	**Quartz $\epsilon_r \sim 4.3$**	73 μm	CPW
Quartz versus GaAs		568 nm	**GaAs $\epsilon_r \sim 12.9$**	73 μm	CPW
Change in transmission line	◇	809 nm	GaAs $\epsilon_r \sim 12.9$	73 μm	**microstrip**
Microstrip versus CPW		1500 nm	GaAs $\epsilon_r \sim 12.9$	73 μm	**CPW**

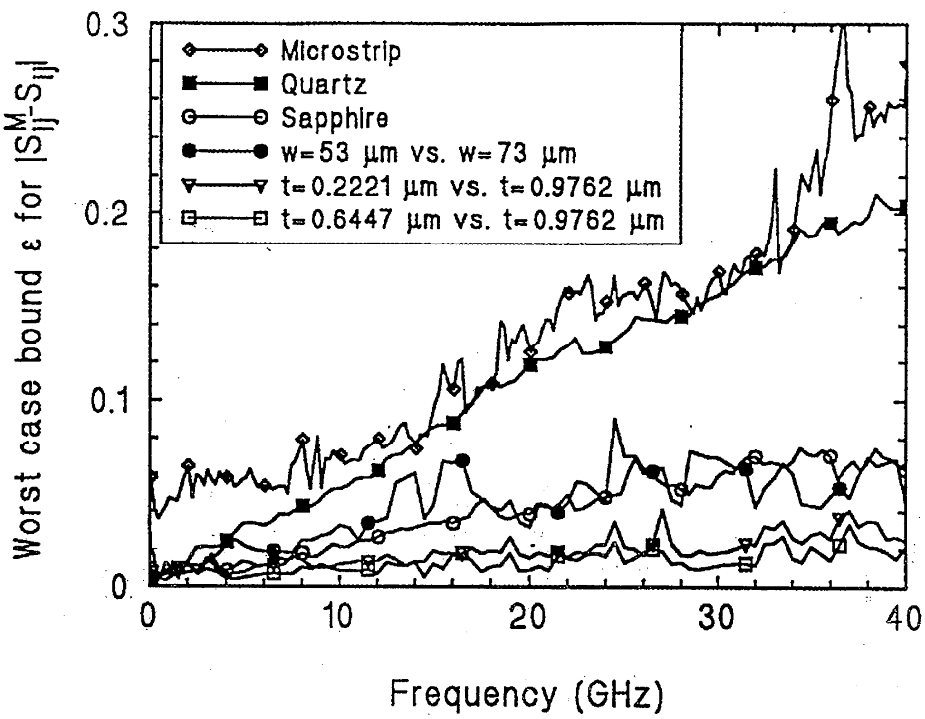

Fig. 2. The worst-case differences between calibrations relating the impedance transformed S-parameters with reference impedance Z_{ref}= 50 Ω at a position 25 μm from the beginning of the lines, which corresponds very nearly to a position at the tips of the microwave probes used to contact the lines. The physical parameters of the lines used to realize the calibrations are summarized in Table 1.