On-Wafer Measurement at Millimeter Wave Frequencies

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***Abstract*- We investigate millimeter wave on-wafer calibration and measurement in coplanar waveguide and demonstrate the applicability of the multiline thru-reflect-line calibration and good measurement repeatability between laboratories. We also investigate calibrations in conductor-backed coplanar waveguide.**

INTRODUCTION

This paper examines the suitability of multiline thru-reflect-line (TRL) calibrations [1] with reference impedance correction [2] in coplanar waveguide (CPW) for millimeter wave measurement. We show that the TRL calibration measures the CPW mode accurately and repeatably to 110 GHz and that neither the calibration nor the measurements exhibit any effects of coupling to or excitation of surface waves. This latter result contrasts with the previously reported results of [3] for CPW of larger transverse dimensions, which showed effects of strong surface wave excitation at and above critical frequencies where the CPW and surface waves are degenerate. We will also show that the TRL

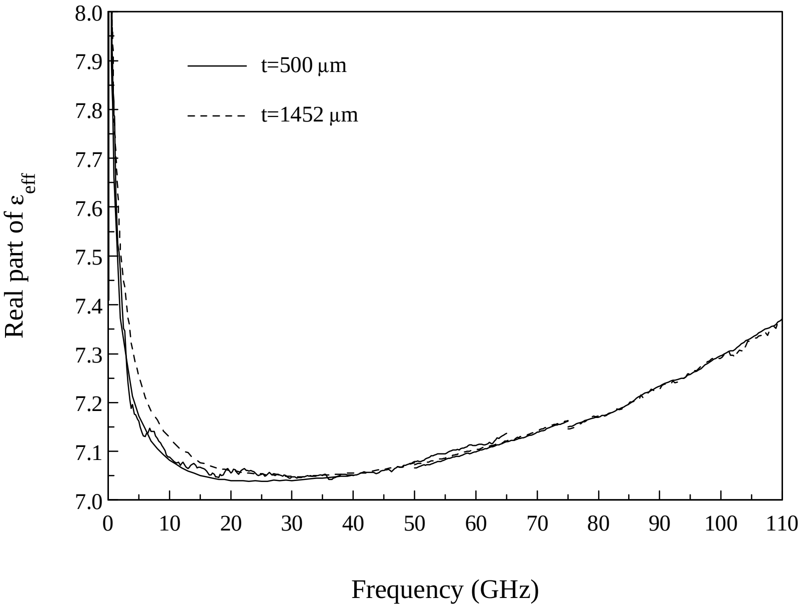

Figure 1. The real part of ϵ_{eff} measured by the multiline TRL calibration on two wafers of different thicknesses t with several different instruments.

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calibration fails in conductor-backed CPW.

MULTILINE TRL CALIBRATION

Figure 1 shows the real part of the effective dielectric constant $\epsilon_{\mathrm{eff}} \equiv -(c\gamma/\omega)^2$, where γ is the propagation constant of the mode measured by the multiline TRL calibration [1], for two CPW transmission lines with 73 µm wide center conductors separated from two 250 µm wide ground planes by 49 µm gaps deposited on gallium arsenide (GaAs) wafers of thicknesses 500 µm and 1454 µm. The values of ϵ_{eff} shown in Figure 1 correspond closely to the quasi-static value $(\epsilon_r+1)/2 \approx 6.95$ of the CPW mode, where ϵ_r, the relative dielectric constant of the GaAs substrate, is about 12.9 [4]. The rise in the real part of ϵ_{eff} at low frequencies is typical of that caused by the series resistance of the thin metal conductors [2], while the slight monotonic increase in the real part of ϵ_{eff} at high frequencies is consistent with the quasi-TEM behavior of the CPW mode. These results indicate that the TRL calibration measures the standard quasi-TEM CPW mode.

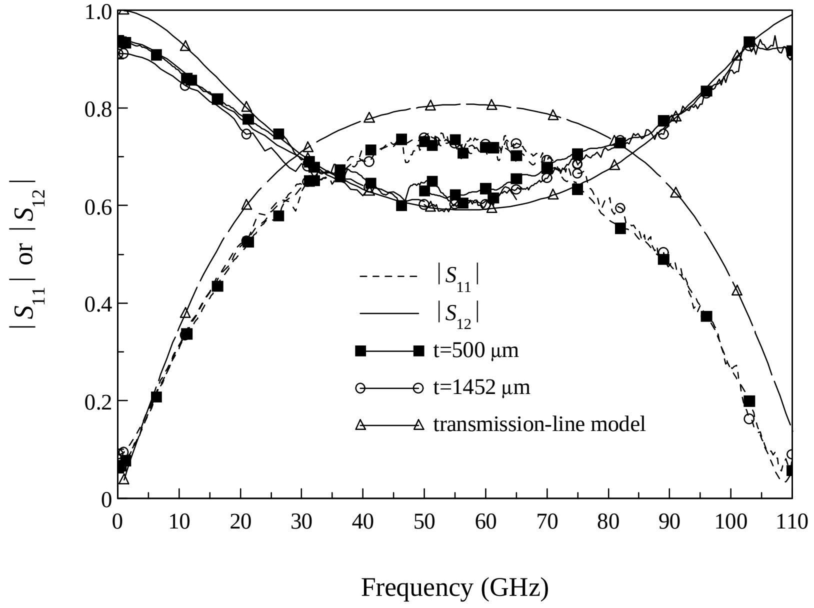

Figure 2. The magnitude of the transmission coefficients (solid lines) and reflection coefficients (dashed lines) of CPW inductors of identical design measured by the multiline TRL calibration on two wafers and by several instruments over different frequency bands.

While scaling the results of [3] indicates that coupling to surface waves is not expected on the 500 µm thick substrate below 100 GHz, this scaling also predicts that several surface waves could couple to and be excited by the CPW mode on the thicker substrate between 40 GHz and 110 GHz. The smooth monotonic form and close agreement of both the real part and imaginary part (not shown in the figure) of ϵ_{eff} measured on the two substrates exhibits no signs of such coupling.

DEVICE MEASUREMENTS

We gathered evidence that surface waves did not effect the calibrations or the lumped behavior of small devices embedded in the CPW lines. Figure 2, which is typical of this study, shows the magnitudes of the scattering parameters of a distributed series inductor in a CPW line. The inductor is formed from a 500 µm long section of high-impedance CPW with 10 µm wide center conductors separated from 10 µm wide ground planes by 185 µm gaps.

The figure compares the measurements to the S-parameters of a lossless 500 µm section of line with characteristic impedance 153 Ω and a normalized propagation constant $\beta/\beta_0=2.637$, values which correspond to calculated quasi-static parameters of the section of high-impedance line. This simple lossless model and the measurements agree fairly well despite the high loss of the narrow conductors in the measured circuit.

The figure shows very close agreement between all of the measurements despite the significant difference in substrate thicknesses. This indicates that only the CPW mode is excited on the two substrates even well above the critical frequencies at which [3] predicts that coupling to surface waves on the thicker substrate could take place. Measurements of other devices on the two wafers were consistent with these observations.

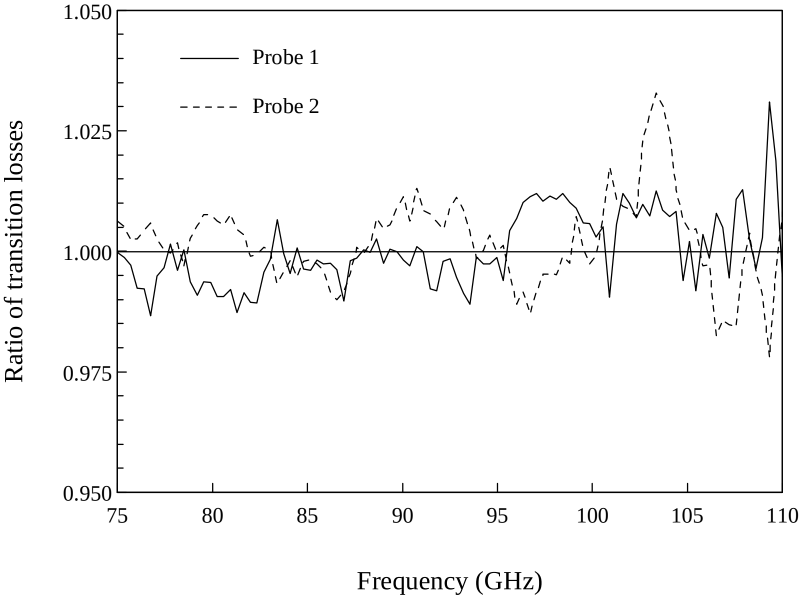

Figure 3. The ratio of the 500 μm and 1454 μm thick substrate probe-tip-to-CPW transition losses.

PROBE-TIP-TO-CPW TRANSITIONS

Any coupling into surface modes at the probe-tip-to-CPW transition on the thick substrate must augment the loss of the transition and could also increase the transmission of energy between transitions. Since we do not expect coupling to surface waves on the thinner substrate, the difference of the losses of the probe-tip-to-CPW transitions on the two wafers determines the energy coupled into surface waves by the transition and line on the thicker substrate.

We used the calibration comparison method of [5] to measure the ratio of the losses of the probe-tip-to-CPW transitions on the two substrates. Figure 3 shows that this ratio differs from 1 by only a few percent, eliminating the possibility that significant energy was coupled into surface wave modes by the probe-tip-to-CPW transition on the thick substrate.

We also checked for an increase in the transmission of energy between probe-tip-to-CPW transitions due to excitation of surface waves on the thicker substrate by examining CPW circuits with low transmission coefficients. Figure 4 shows the measured transmission between a short-circuit embedded in a CPW

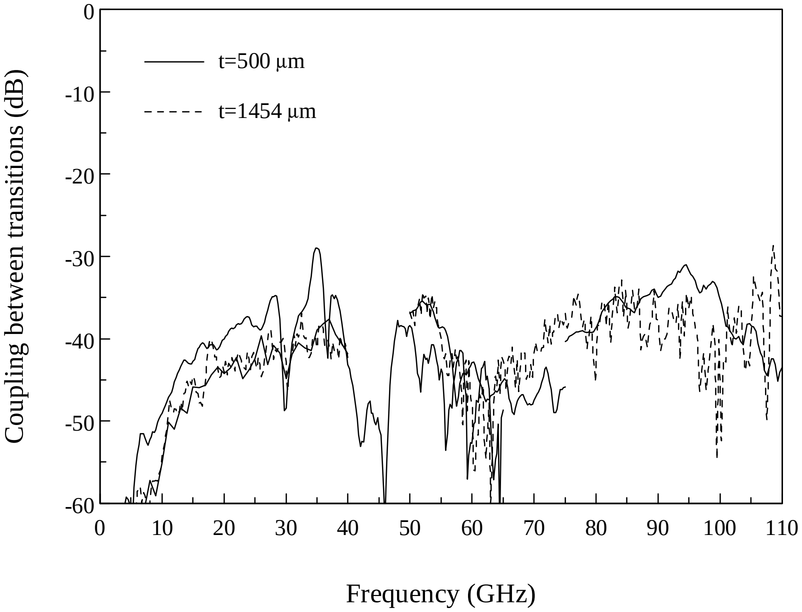

Figure 4. Coupling between transitions on wafers of thickness t.

separated by 500 µm from a CPW open. The test structure is 1050 µm long, so the probe-tip-to-CPW transitions were separated by about 1 mm during the measurement. The figure shows that the differences in transmission on the two substrates are small, which indicates that transmission between transitions was not increased by coupling to or excitation of surface wave modes on the thicker substrate. We found similar results for a number of loads, attenuators, and other low-transmission devices we tested.

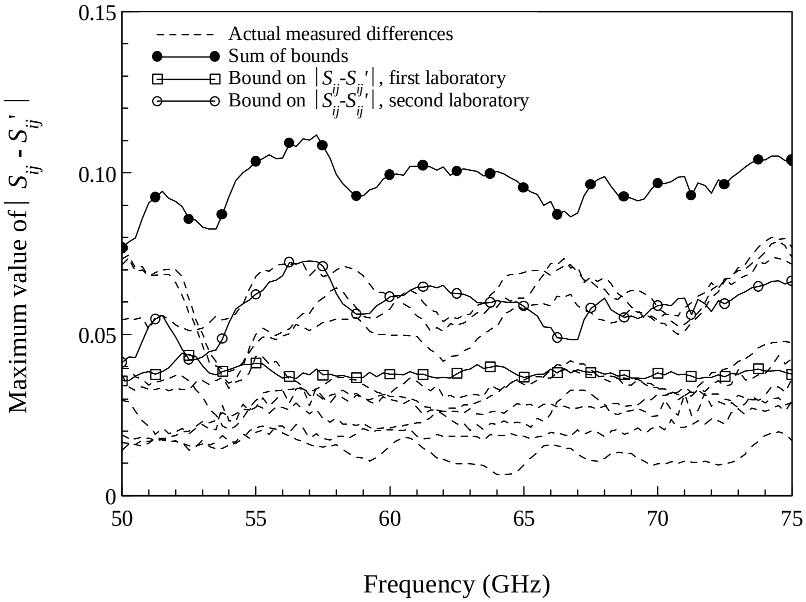

Figure 5. Worst case measurement differences at V-band for nine small passive devices tested at two different laboratories and bounds on the measurement errors.

MEASUREMENT REPEATABILITY

Figure 5 plots the magnitude of the differences of measurements of nine simple passive circuits performed in two different laboratories. The dashed lines in the figure are the largest differences $|S_{ij} - S'_{ij}|$ for $ij \in \{11, 21, 12, 22\}$, where S_{ij} was the scattering parameter measured at one laboratory and S'_{ij} was the scattering parameter measured at the other. The figure also shows bounds on the measurement errors due to instrument drift determined by the calibration comparison method of [5] at each of the laboratories. The small measurement differences and low error bounds show that the measurements performed at the laboratories were highly repeatable.

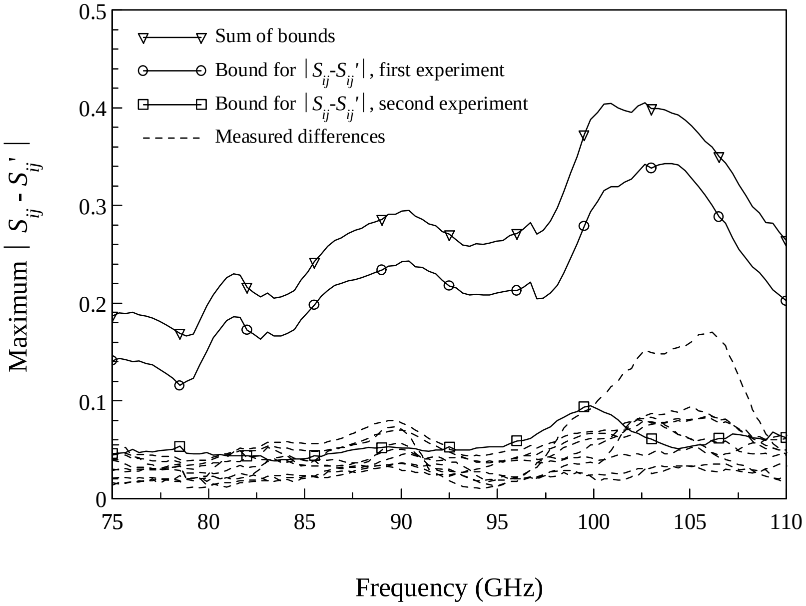

Figure 6. Worst case measurement differences at W-band for nine small passive devices tested twice at a single laboratory and bounds on the measurement errors.

Figure 6 shows the results of a similar experiment at W-band, except that in this case the two sets of measurements were both performed at the same laboratory. While the instrument drift during the first of the two experiments was large, the instrument drift during the second experiment and differences between device measurements are comparable to the V-band results of Figure 5. This indicates that the accuracy of the second calibration and measurements were comparable to those in the V-band experiment.

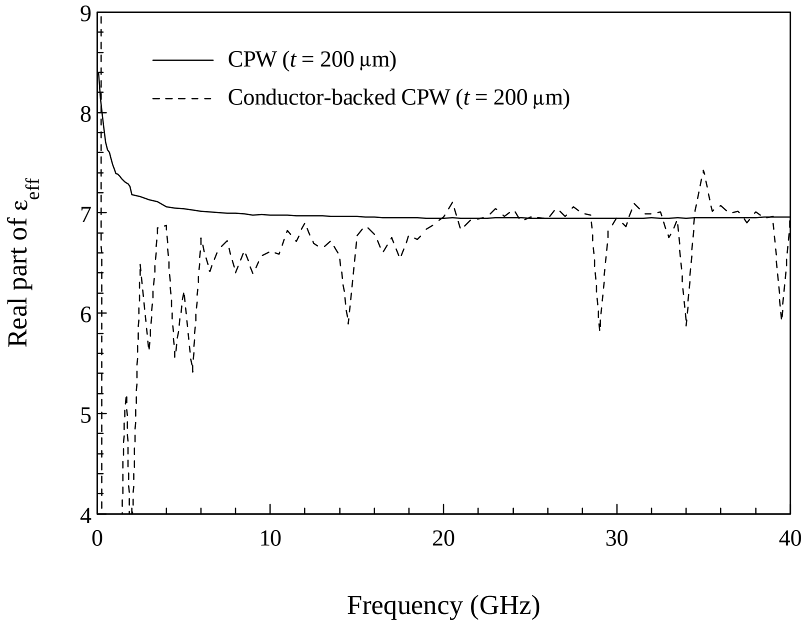

Figure 7. The real part of $\epsilon_{\rm eff}$ measured by the multiline TRL calibration in CPW and conductor-baked CPW on a 200 μm thick GaAs substrate.

CONDUCTOR-BACKED CPW

We also explored measurements in conductor-backed CPW, a popular coplanar transmission line with a ground plane on the back of the substrate. We did not connect the CPW ground planes to the ground plane on the back of the substrate with via holes in our experiments. Figure 7 shows the real part of $\epsilon_{\rm eff}$ measured by the multiline TRL calibration for both CPW and conductor-backed CPW fabricated on the same wafer, achieved by patterning the ground plane on the back of the 200 μm thick substrate. While the CPW measurement is smooth and follows the expected behavior of the CPW mode, the propagation constant measured on the conductor-backed CPW line does not correspond to that expected of the CPW mode. This may be due to coupling to a "microstrip-like" mode of propagation in the conductor-backed CPW, a mode which is unaccounted for by the TRL calibration.

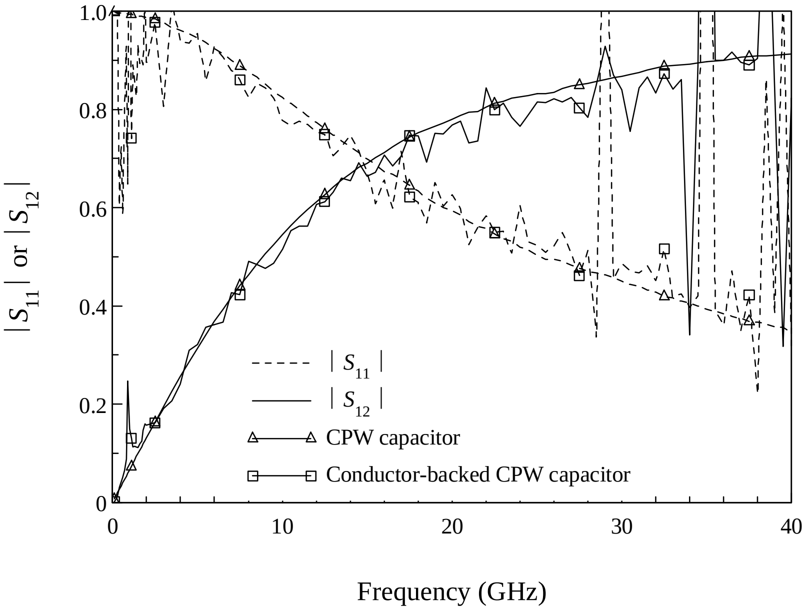

Figure 8. Measured scattering parameters of small lumped capacitors embedded in CPW and conductor-backed CPW.

Figure 8 shows measurements of a series capacitor. The reflection coefficient is shown in dashed lines and the transmission coefficient in solid lines. The measurements marked with triangles are those of a capacitor embedded in CPW and performed with a multiline CPW TRL calibration. They are smooth and well behaved, as we would expect for a small lumped capacitor at these frequencies. The figure compares them to measurements of a capacitor of identical design embedded in conductor-backed CPW, which are marked by squares and were performed with a conductor-backed CPW TRL calibration. In contrast to our CPW measurements, the conductor-backed CPW measurements are not smooth and well behaved as we would expect, another indication that the conductor-backed CPW TRL calibration failed.

CONCLUSION

Our experiments show that the multiline TRL calibration yields high-quality repeatable measurements of the CPW mode up to 110 GHz in our CPW transmission lines, even above the critical frequencies at which [3] predicts that coupling to surface waves could take place. We were unable to find evidence that surface waves adversely affected either the calibrations or the performance of small passive devices or that they increased the loss of or the coupling between probe-tip-to-CPW transitions. We showed, however, that the TRL calibration fails in conductor-backed CPW lines even at low frequencies.

REFERENCES

[1] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," *IEEE Transactions on Microwave Theory and Techniques* 39, pp. 1205-1215, July 1991.

[2] R. B. Marks and D. F. Williams, "Characteristic Impedance Determination using Propagation Constant Measurement," *IEEE Microwave and Guided Wave Letters* 1, pp. 141-143, June 1991.

[3] E. M. Godshalk, "Surface wave phenomenon in wafer probing environments," *40th ARFTG Conference Digest*, pp. 10-19, Dec. 1992.

[4] E. J. Vanzura, C. M. Weil, and D. F. Williams, "Complex permittivity measurements of gallium arsenide using a high-precision resonant cavity," *Proceeding of the 1992 Conference on Precision Electromagnetic Measurements*, pp. 103-104, 1992.

[5] D. F. Williams, R. B. Marks, and A. Davidson, "Comparison of On-Wafer Calibrations," *38th ARFTG Conference Digest*, pp. 68-81, Dec. 1991.