Radiation, Multimode Propagation, and Substrate Modes in W-Band CPW Calibrations

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***Abstract* — We investigate the degradation of the accuracy of coplanar waveguide calibration standards at higher frequencies due to multi-mode propagation, substrate modes, and radiation. Based on a typical calibration substrate, we investigate these effects and their impact on vector-network-analyzer calibrations at W-band.**

Keywords* — *calibration, CPW, em simulation, on-wafer, measurements.

I. Introduction

Measurements in the microwave frequency range require calibration with well-characterized calibration structures. The electrical behavior of these calibration structures needs to be well known and one must be able to measure them with high accuracy, since any uncertainty in the calibration structures will be propagated to the calibrated measurements. Typically an "off-wafer" calibration substrate, which contains coplanar-waveguide (CPW) transmission lines of different lengths, short and open stubs, and resistive loads, is used.

With increasing frequency, radiation becomes more important. Moreover, the environment, including the mechanical support on which the calibration set (and the DUT) is placed, are important, since they may also give rise to unwanted moding or resonances. Multi-mode propagation is also critical, since the common calibration procedures assume only single-mode propagation, and any additional modes influencing the measurements will degrade accuracy. In a coplanar environment, this applies particularly to the parallel-plate mode, which is sometimes referred to as a "microstrip mode." This mode is caused by an overall voltage difference between the three CPW conductors and the metalization on the back of the substrate.

The purpose of this paper is to shed some light onto these parasitic effects when measuring coplanar structures in W-band and above. Based on the understanding of the underlying phenomena, suggestions are presented on how to avoid or minimize them and how to design improved calibration sets for frequencies in the 100 GHz range.

II. Practical Example

We begin with simulations of a typical commercially available calibration substrate. This substrate is currently used at frequencies as high as 110 GHz for multi-line thru-reflect-line (TRL) calibrations [1].

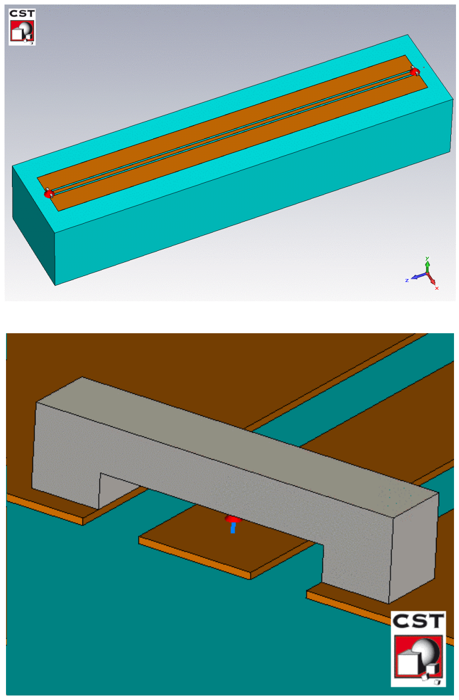


Fig. 1. The CPW transmission-line section analyzed (top) and the port description used in electromagnetic simulation (bottom) (blue lines with red arrows denote lumped ports).

Included in this set are CPW transmission-line sections of different lengths (200 µm, 450 µm, 900 µm, 1800 µm, 3500 µm and 5250 µm) and a pair of CPW short stubs. These structures were both measured and simulated, employing the

978-2-87487-022-4

3D finite-difference electromagnetic field solver Microwave Studio [2][1].

We illustrate one of the investigated CPW lines (50 µm wide center conductor, 25 µm wide gap, 275 µm wide ground plane and 3 µm thick metallization) in Fig. 1. The substrate thickness was 250 µm (with a dielectric constant εr = 9.9) and the set is placed on a wafer-prober chuck. We applied an internal port description to model the probe that makes use of the conducting bridge between the ground planes of the coplanar waveguide shown in Fig. 1. A similar excitation model was used in [3] for HFSS simulations.

Fig. 2 presents the attenuation data of the CPW line we extracted using the multiline TRL algorithm from our simulations of each calibration standard as well as from our direct measurements of the calibration standards.

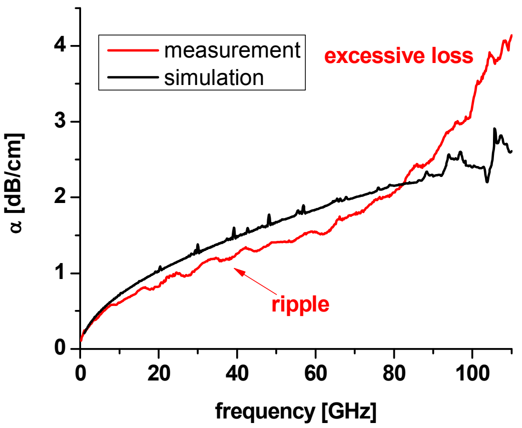


Fig. 2. Measurements and simulation data for extracted line attenuation as a function of frequency.

Two effects can be observed that cannot be explained by a single-mode CPW model. First, the measured curve exhibits some ripple at frequencies below 50 GHz that does not appear in the simulation. Second, we observe a strong increase of attenuation for frequencies above 80 or 90 GHz.

III. ATTENUATION RIPPLE

The ripple in the attenuation data shown in Fig. 2 may be caused by multi-mode propagation. Conductor-backed coplanar waveguides support both the conventional coplanar waveguide mode and a slot mode that is suppressed by symmetry, and a parallel-plate mode [4]. The parallel-plate mode supports a potential difference between the conductors on top of the substrate and the conductor on the back of the wafer. In order to investigate the hypothesis that generation of the parallel-plate mode is responsible for the ripple in the attenuation observed in Fig. 2, we first investigated how strongly the port in Fig. 1 excites the parallel-plate mode. Fig. 3 presents the level of coupling from our ports into the parallel-plate mode for substrate thicknesses of 50 µm and 250 µm. As can be seen from the figure, we have coupling coefficients in the –40 dB range. Coupling to the parallel plate mode at this level will cause only minor influence on the first order transmission-line quantities, i.e., phase constant and real part of characteristic impedance. This coupling will not severely affect the overall calibration, but it may have significant influence on sensitive quantities such as attenuation.

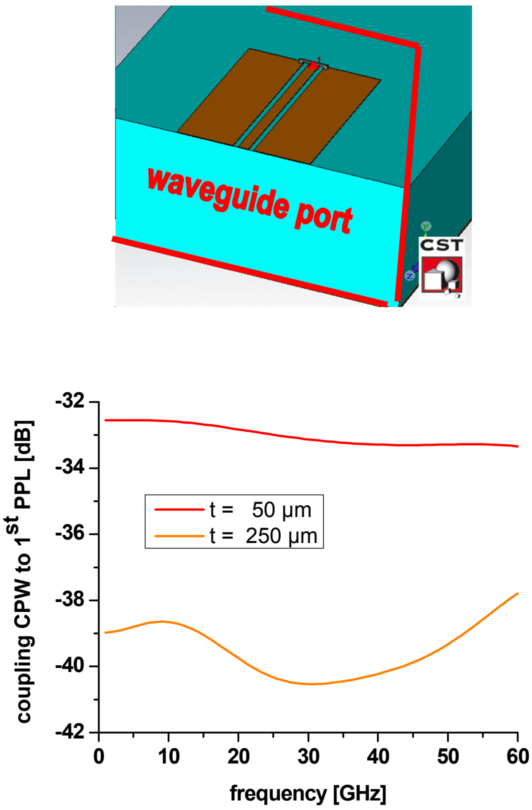


Fig. 3. Excitation of the parallel-plate mode using the port according to Fig. 1: Geometry (top) and coupling frominput into parallel-plate mode against frequency, with substrate thickness as a parameter (bottom).

Assuming that parallel-plate mode propagation plays a role, the next step is to make sure that the termination conditions at the ports are the same for measurements and simulations. For the port shown in Figs. 1 and 3, the parallel-plate mode is terminated by an approximated open, since the conductors on top of the substrate end without any connection to the ground on the backside.

The measurement situation is illustrated by Fig. 4, which shows the model we employed for our probe tips. Unlike the electromagnetic simulation port discussed earlier, a parallel-

[1] We used brand names only to better specify the experiments and simulations we performed. NIST and PTB do not endorse commercial products. Other products may work as well or better.

plate mode incident from the CPW section to the tip will not see an open termination here, but will continue to propagate into the substrate below and behind the probe tips, with fields extending between the outside conductor of the coaxial cable and the ground plane below the substrate. The absorbing material, which is commonly mounted on the outer part of the coaxial cable, has strong influence on this mode and will cause attenuation. Thus, we expect that the input impedance of the tips has a considerable real part.

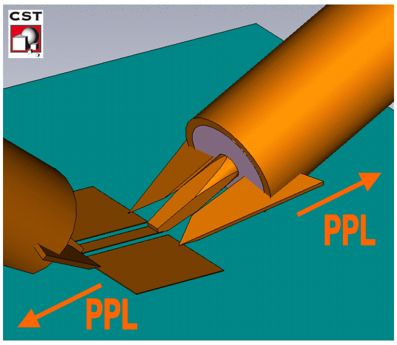


Fig. 4. Probe tip structure (note that in practice the outer conductor of the coaxial cable commonly is covered with absorbing material).

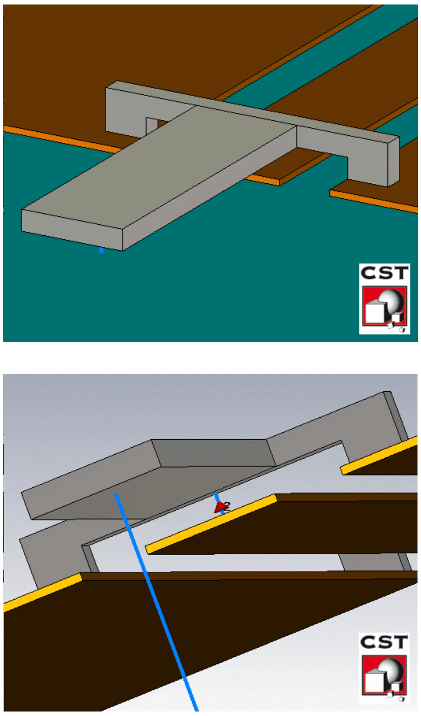


Fig. 5. Modified port structure used in the electro-magnetic simulation with lumped impedance between CPW metallization and the conductor supporting the substrate.

To better simulate the measurement situation, we redefined the port of Fig. 3 by adding a (lumped) impedance Z_{PPL} between the top CPW metallization and the conductor supporting the substrate, as illustrated in Fig. 5.

The value of Z_{PPL} was chosen to be 30 Ω, which is close to the characteristic impedance of the parallel-plate mode for this geometry. Then the different CPW sections forming the calibration set were resimulated with this port, and the multi-line extraction algorithm was applied as before. Fig. 6 presents the resulting attenuation data, which can be compared directly to the attenuation data plotted in Fig. 2.

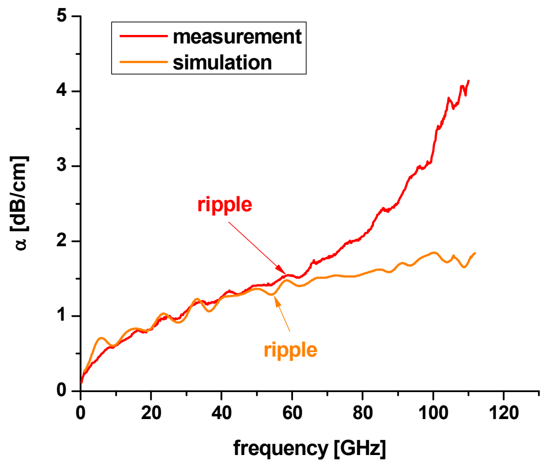


Fig. 6. Measurements and simulation data for extracted line attenuation as a function of frequency: data of Fig. 2, but with the modified port of Fig. 5 used in the electro-magnetic simulation.

The figure shows that terminating the parallel-plate mode with 30 Ω termination impedance leads to exactly the ripple on the alpha curve observed in measurements. This indicates that the ripple effect is indeed caused by the propagation of the parallel-plate mode. However, it does not explain the increased loss at higher frequencies, which will be discussed in the following section.

IV. Excessive High-Frequency Loss

The simulation and measurement results in Fig. 6 are qualitatively quite similar. Both exhibit a strong increase of attenuation at high frequencies. However, the differences are still rather large, as the frequencies at which the steep increase starts (80 GHz and 120 GHz, respectively) differ by about 40 GHz.

The simulations indicate that the loss increase is related to resonances of the first higher-order parallel-plate mode, which strongly radiates into surface waves on the substrate. The electric field pattern shown in Fig. 7 illustrates this, where the vertical component is plotted in a horizontal plane 10 µm below the top surface of the 50 µm thick substrate at 147.8 GHz.

The field pattern clearly shows the presence of two modes: The CPW mode is visible with the field maxima (dark lines) in the center between the two CPW ground planes, while the maxima at the outer edges of the ground planes are characteristic of the first higher-order parallel-plate mode. This mode couples strongly to the surface waves on the substrate (TE_{01} surface wave mode in [5]), thus radiating power and causing the increased attenuation of the CPW.

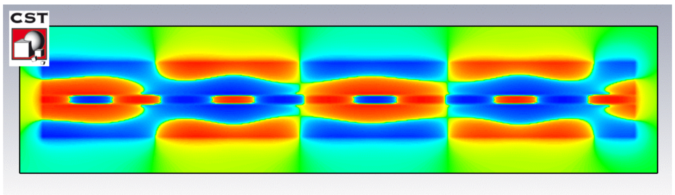
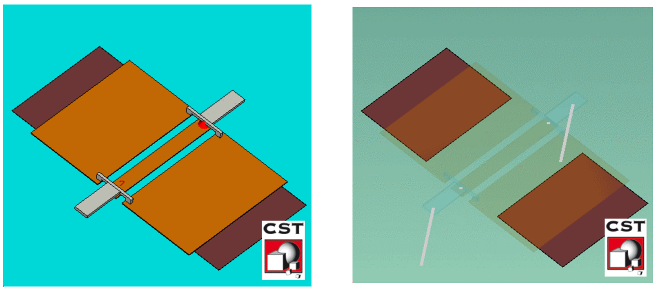


Fig. 7. Vertical electric field in the substrate 10 µm below the top surface of the 50 µm thick substrate at 147.8 GHz.

Although these effects appear to be significant, an in-depth study revealed that they cannot be the sole reason for the loss increase seen in Fig. 2 at frequencies above 70 GHz. We need an additional loss mechanism to fully explain it.



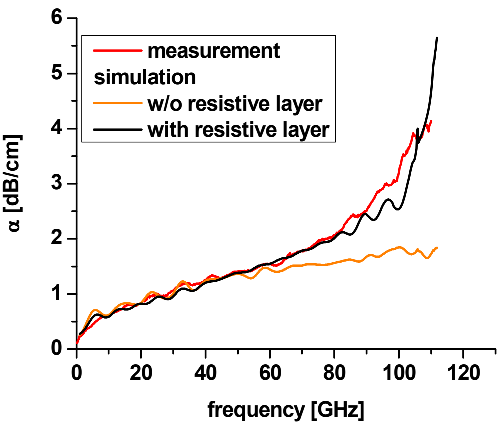


Fig. 8. Measurement and simulation data for extracted line attenuation as a function of frequency: data of Fig. 6, but with a resistive layer around the outer part of the CPW metallizations used for electromagnetic simulation.

Further investigation showed that this additional loss was due to resistive layers placed around the CPW structures, which is common practice for W-band calibration substrates. These layers are located at the outer edges of the CPW ground metallization, just below the metal and extending 100 µm beyond the ground planes. The idea is to suppress parallel-plate-like modes without perturbing the desired CPW mode, whose field is concentrated in the gaps around the CPW center conductor.

Fig. 8 illustrates what happens if such a resistive layer is introduced. While at lower frequencies the attenuation remains unchanged, there is a strong increase in attenuation above 70 GHz. The agreement between simulation and measurement can be further improved by adjusting the conductivity of the metal, which we estimated from published values. Thus it appears that the excessive loss can be explained by a combination of the resistive layers and the appearance of higher-order parallel plate modes.

V. Conclusions

We showed that the accuracy of common CPW calibration sets at W-band are compromised by the existence of (parasitic) parallel-plate modes and resistive films placed around the CPW calibration structures. This shows up as ripples in the extracted attenuation data below 50 GHz as well as peaks in attenuation at W-band and beyond. These suggest that the accuracy of these calibration sets might be improved by increasing the substrate thickness and decreasing the width of the CPW center conductor, gaps, and ground-plane widths to reduce the interaction with the parallel-plate mode.

Resistive layers, commonly applied to suppress parallel-plate modes in the substrate help to decrease the quality factor of such resonances. But at the same time, they cause additional loss for the CPW line at W-band frequencies and may even reduce the frequencies of resonances. Since the resulting attenuation deviates from the value of the unperturbed CPW, this may degrade calibration accuracy as well.

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