Progress Toward MMIC On-wafer Standards*

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Abstract

A prototype standard set in coplanar waveguide suitable for the calibration of wafer probe stations has been developed through a cooperative effort between the National Institute of Standards and Technology and a MIMIC Phase 3 team. The coplanar standard set is intended primarily for in-process testing, although the characterization of coplanar waveguide circuits is also possible. In this paper two sources of systematic errors associated with the prototype standard set, the propagation of undesirable modes, and the influence of adjacent structures on the electrical connection to the elements of the standard set, will be discussed.

Introduction

As the cost of monolithic microwave integrated circuits (MMICs) has decreased, the proportion of the total circuit cost due to testing and characterization has increased. Manufacturers are increasingly relying on on-wafer testing to reduce total circuit cost. Circuit cost is reduced both by the great efficiency of circuit characterization and by a reduction in fabrication costs associated with early detection of low processing yields.

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On-wafer scattering parameter (S-parameter) calibrations are conventionally based on standard substrates which may be different from that of the device under test. In addition to differences in substrate composition, there may also be differences in metal conductivity and structure geometry. This has given rise to concern that systematic measurement errors may be introduced into the calibration. There has also been concern in the industry that calibrations which rely on lumped standards may be inaccurate if all of the characteristics of the lumped elements are not known.

For these reasons, prototype coplanar waveguide (CPW) and microstrip standard sets are being developed for calibrating wafer probe stations and associated ANA's for measuring S-parameters on gallium arsenide (GaAs) wafers. This effort has been supported by the MIMIC Phase 3 program and by the National Institute of Standards and Technology (NIST). The MIMIC Phase 3 team members[1] collaborated on the development of test structures and measurement techniques, standard set design, and laboratory measurements. Calibration algorithms were developed by NIST.

By fabricating the calibration standards on the same wafer as the devices to be tested, differences in substrate composition, etc. are avoided. The use of lines rather than lumped standards assures that actual S-parameters are measured. The prototype standard set was designed to allow the intercomparison of devices and circuits fabricated on different wafers and to be compatible with planned package characterization standards.[2] The experimental techniques for wafer-to-wafer intercomparison and package characterization are still under development at NIST.

In any S-parameter standard set based on standard transmission lines, three fundamental assumptions must be made. They are that the lines are uniform in the propagation direction, that the lines support only one mode of propagation, and that the electrical connection to the lines is repeatable and unaffected by adjacent structures. The assumption that the lines are uniform in the direction of propagation is fairly well satisfied in this case by the photolithographic method of construction. The repeatability of connection has been treated elsewhere.[3] The other assumptions depend on both the measurement system and the standard set itself and are the subject of this paper. It may also be desirable to understand various properties of the fundamental mode of propagation such as characteristic impedance. Such considerations are beyond the scope of this work.

Prototype Coplanar Waveguide Standard Set

The prototype CPW standard set is pictured in Figure 1. It is based on CPW transmission lines fabricated from 1.5 μm gold conductors evaporated on 500 μm thick GaAs substrates. The CPW lines are composed of a 73 μm wide center conductor spaced 49 μm from two outer ground planes of width 250 μm. The prototype standard set consists of a thru line, four lines which are 2.135 mm, 3.2 mm, 6.565 mm, and 19.695 mm longer than the thru line, and two offset shorts. The CPW lines have a nominal impedance of 50 Ω. During measurement, the substrates are supported on a quartz spacer of 2 mm or greater thickness.

The standard set was designed for use with a Thru-Reflect-Line (TRL) calibration algorithm developed at NIST.[4] The calibration algorithm is based on a rigorous statistical method for optimally determining calibration error coefficients. No attempt is made to correct for the effects of probe-to-probe coupling, although coupling internal to the analyzer is accounted for by the calibration algorithm. The prototype standard set, when used in conjunction with this calibration algorithm, can be used to calibrate wafer probe stations and the associated ANA from a few hundred megahertz to 40 GHz. The addition of a fifth line of longer length is needed if accurate calibrations below a few hundred megahertz are desired.

Some of the elements of the prototype standard set are shown in detail in Figures 2-5. Figure 2 contains a close-up view of the probe contact area. Figures 3, 4, and 5 contain drawings of the thru line and the two offset shorts. The four lines are identical to the thru line except for their additional length.

As shown in Figure 2, three pairs of 5 μm by 5 μm alignment marks were added to the probe contact area to allow for the accurate positioning of the probe tips. For a 50 μm (2 mil) overtravel, the probe tips can be aligned to the first pair of alignment marks before lowering the probe heads. The probe tips will then skate to a position near the second pair of alignment marks as the probe heads are lowered. The probe heads can then be aligned accurately to the second pair of alignment marks, as shown in the figure. Aligning the probe tips to the third pair of alignment marks may be more convenient if a 100 μm (4 mil) overtravel is used. The actual probe tip position chosen will not, of course, affect the measurements as long as the probe tips are positioned in the same way during both calibration and measurement.

The plane to which all measurements are referenced, which we call the on-wafer reference plane, is located at a position 275 μm from the end of the lines, as illustrated in Figure 2. This on-wafer reference plane corresponds to the center of the thru line shown in Figure 3. This is the natural reference plane for a TRL calibration.

Modes of Propagation

We identified several possible modes of propagation in coplanar waveguide: the coplanar mode, a microstrip mode, a slot mode, and various surface and free-space modes of propagation. In the coplanar mode of propagation, the CPW center conductor serves as the signal conductor while the two outer CPW conductors serve as the grounds. This is the desired mode of propagation.

The existence of only a single mode of propagation in the transmission line is required in order to completely characterize the interaction of a circuit and the transmission line by means of S-parameters alone. The presence of other modes of propagation violates this condition and is the first object of our investigation. We measured the coupling between our probe heads in a series of experiments in which one or more of these modes could propagate.

Free-space modes do not require any structures for propagation. Surface-wave modes require only the substrate and ground plane to propagate. The microstrip mode of propagation is usually thought of as requiring the metal ground plane under the substrate, which serves as the ground for the mode, and the center conductor and/or the outer CPW ground planes to serve as the signal conductors. This mode does not require gaps in the metalization to propagate. Shigesawa, et al.[5] have shown that this mode can propagate even when the ground plane is removed far from the guide. The slot mode of propagation requires the two coplanar ground planes to serve as the positive and negative signal lines while the CPW center conductor assumes zero potential. This mode requires only a single gap in the metalization to propagate.

We measured the coupling of free-space modes of propagation radiated between our probe heads by suspending our probe heads in the air and measuring the transmission between the probe heads as a function of the probe head spacing. In this experiment there were no conductors and no substrate present, so the coplanar, microstrip, surface-wave, and slot modes cannot propagate. The worst case coupling from 50 MHz to 40 GHz is shown in Figure 6 and is labeled "air." The probe head separation on the horizontal axis is defined as that separation required to contact a CPW line of the length shown on the horizontal axis of the figure. This coupling is low and is the value usually quoted by probe vendors. As we shall see, other coupling modes dominated this one in many of our experiments.

We measured surface-wave coupling by contacting the bare substrate with the probe tips. In this experiment both free-space and surface-wave modes can propagate. The microstrip, coplanar, and slot modes cannot propagate because there are no conductors present to support those modes. These coupling levels, labeled "surface wave" in Figure 6, were measured both with and without the quartz spacer supporting the substrate.

When a quartz spacer was used to support the substrate, the wafer chuck ground plane was removed from the bottom of the substrate by the intervening spacer. When the quartz spacer was absent, the substrate was supported directly by the wafer chuck ground plane. In both cases the measured coupling was significantly higher than the coupling through free-space modes, indicating that most of the coupling was due to surface waves, not free-space modes. Furthermore, the surface-wave coupling was significantly higher when the quartz spacer was not used, presumably due to the proximity of wafer chuck ground plane to the substrate.

We attempted to measure the coupling through the microstrip mode by contacting a single rectangular pad of metal on the surface of the substrate with both probe tips. In this experiment, neither the coplanar nor the slot modes may propagate, because there are no gaps in the metalization, but the free-space, surface-wave, and microstrip modes may propagate. The worst case coupling is shown in Figure 6 both with and without the quartz spacer supporting the wafer.

In the microstrip coupling experiment in which the quartz spacer was used to support the substrate, the coupling was significantly higher than the coupling when only the surface-wave and free-space modes were present. Because it is not possible to determine the relative contributions to the coupling mechanisms in this experiment, we can only assume that some combination of the surface-wave and microstrip coupling is responsible for the total coupling measured in the experiment.

In the microstrip coupling experiment in which the quartz spacer was not used, the measured coupling was significantly higher than in the same experiment with the quartz spacer and in the surface-wave experiment without the quartz spacer. Again, we cannot determine which of the propagating modes are responsible for the increased coupling in this experiment. We postulate, however, that the microstrip mode would be most greatly affected by the proximity of the ground plane, and thus would be most likely to be responsible for this measured rise in coupling when the quartz spacer is not present.

We attempted to measure the coupling through the slot mode by contacting a 200 μm slot in a ground plane with our probes. In this experiment the grounds of our ground-signal-ground probes contacted two outer conductors while the signal contact was placed directly in the center of the gap on the bare substrate. We then measured and plotted the worst case coupling, labeled "slot," in Figure 6 both with and without the quartz spacer present. In this case, only the coplanar mode may not propagate; the slot, microstrip, surface-wave, and free space modes may propagate. Thus the total coupling is caused by some combination of these modes.

When the quartz spacer was present, the measured coupling was similar to the coupling in the microstrip case. We thus concluded that little additional energy is coupled from probe to probe in the slot mode when the quartz spacer is used to support the substrate.

In the absence of the quartz spacer, the coupling is significantly below the coupling in the microstrip case with no quartz spacer, even though an additional mode can propagate. This result is contrary to our intuition and may be caused by a suppression of coupling into the mode when the probe signal contact is not shorted to the probe ground contacts, to a reduced coupling when metal is not present directly underneath the probe arm, or to cancellation of coupled amplitudes. Understanding this result will require further experiments in which various modes of propagation are clearly identified and the coupling due to each mode is fully separated in the measurement.

We performed other experiments to detect the presence of a slot mode in our CPW lines. In one experiment a 100 μm wide conductor underneath the probe arm shorted the two CPW ground planes. We first compared the measured S-parameters of the thru line to another line in which a narrow slot broke the conductor shorting the ground planes. In the absence of a slot mode, the break is not expected to alter the measured S-parameters significantly. In the presence of the slot mode, the break in the ground strap might be expected to provide a very different terminating impedance. In this experiment we found no measurable difference between the thru lines with and without the slots.

We also tried to test for the presence of a slot mode by launching the coplanar mode in a CPW line with a ground-signal-ground probe and probing the opposite end of the line with a two-contact ground-signal probe contacting the two outer ground planes only. If there was significant energy in the slot mode of propagation we would expect to detect that energy with the ground-signal probe. In this experiment we were unable to detect any energy in the slot mode above the microstrip coupling level, which was measured in a separate experiment to be about -30 dB. Like the slot experiment (see curves labeled "slot" in Figure 6), these experiments indicate that there is less energy in the CPW slot mode than in the surface-wave and microstrip modes.

Figure 6 indicates that, at a probe head separation of 500 μm or greater, the worst-case probe-to-probe coupling when a quartz spacer is employed is below -38 dB. This was the motivating factor behind the choice of thru length (550 μm) in the prototype calibration set. In Figure 7 we have plotted the worst-case probe-to-probe coupling for this probe head separation measured in the experiments described above over various frequency bands. This plot indicates that at lower frequencies the use of a quartz spacer is not required, but at higher frequencies probe-to-probe coupling can be reduced significantly by using a quartz spacer to support the substrate.

Influence of Adjacent Structures

The assumption that the electrical connection to the CPW lines is consistent is fundamental to the calibration process. The repeatability of the electrical connection of microwave wafer probes to a single structure has been thoroughly studied and is treated in literature from various probe station vendors.[3] The influence of adjacent structures on such connections has not, and was the second subject of our investigation. We thought that such a study was necessary because in separate experiments with microstrip lines and probe tip-to-microstrip transitions utilizing via-holes to connect the grounds, we observed that structures placed under the probe arm can couple strongly to the probes and greatly affect the measurements. The nature of this coupling in these experiments depended on the probe itself, on the coupling geometry, and on the resonant behavior of the adjacent circuit.

We evaluated the coupling of structures under our probe arms by fabricating 500 μm by 670 μm rectangular conductors at 300 μm, 400 μm, and 500 μm from the beginning of a CPW thru line. In this experiment, we were unable to measure any difference in the S-parameters of the thru line caused by the proximity of the rectangular conductors underneath the probe arm to the line. We also placed long resonant CPW lines under the probe arms at 500 μm, 600 μm, and 700 μm from the beginning of a CPW thru line. Again, we were unable to measure any effects on the measured S-parameters of the thru line. This indicates that resonant structures such as long CPW lines can be placed under the probe tips at least as close as 500 μm and passive structures can be placed at least as close as 300 μm from the beginning of CPW lines without affecting the measurements.

Conclusion

Experiments designed to investigate the fundamental assumptions of a single mode of propagation in and the ability to make consistent electrical connections to prototype coplanar standards developed as a collaborative effort between NIST and a MIMIC Phase 3 team were described. The worst case probe-to-probe coupling from 50 MHz to 40 GHz due to other modes of propagation was shown to be better than -38 dB for a 550 μm probe head spacing when the substrate is supported by a quartz spacer. This worst-case coupling rose to approximately -32 dB when no quartz spacer was employed. The ability to contact the lines repeatably was not degraded by structures placed as close as 300 μm from the beginning of the coplanar lines.

References

1. The MIMIC Phase 3 team members were Ball Aerospace, Cascade Microtech, the University of Arizona, and the National Institute of Standards and Technology (NIST).

2. K. Phillips and D. Williams, "MMIC package characterization with active loads," 36th Automatic RF Techniques Conference Proceedings - Monterey California, November 29-30 1990.

3. "Introducing the world's first microwave wafer robing equipment," product bulletin from Cascade Microtech, Inc., Beaverton OR.

4. R. Marks, "A multi-line calibration for MMIC measurement," 36th Automatic RF Techniques Conference Proceedings - Monterey California, November 29-30 1990.

5. H. Shigesawa, M. Tsuji, and A. Oliner, "A new mode-coupling effect on coplanar waveguides of finite width," IEEE Microwave Theory and Techniques International Microwave Symposium Digest, Vol. 3, pp. 1063-1066, May 1990.

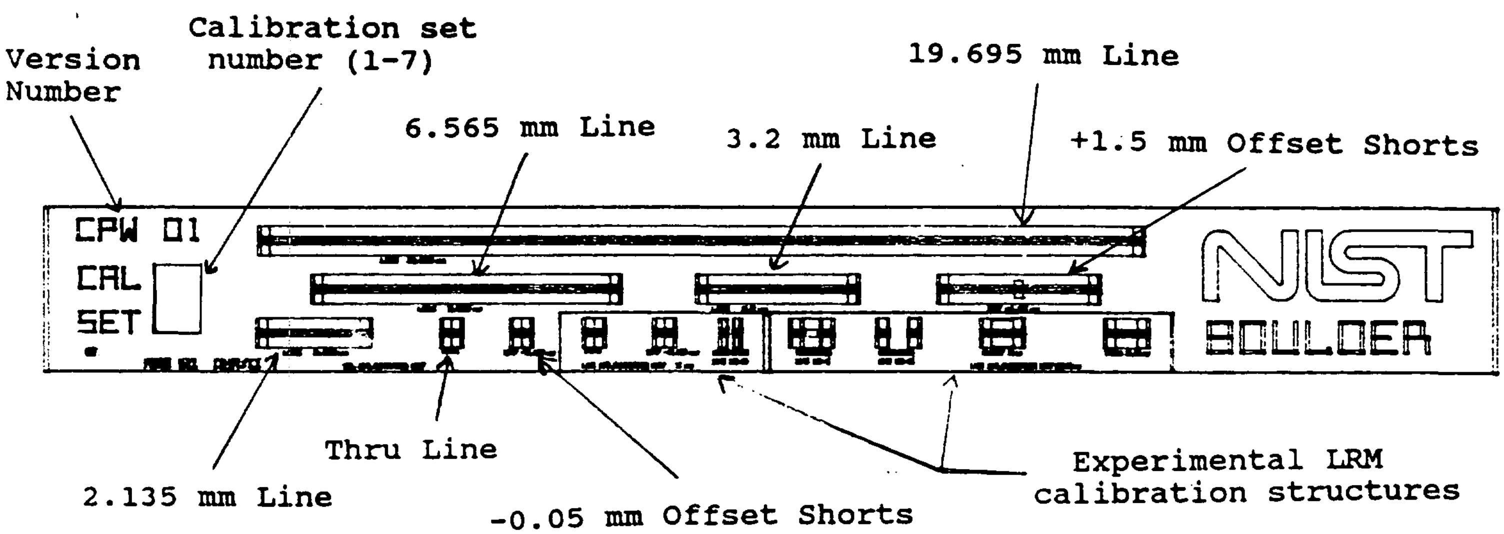


Figure 1. The proposed coplanar waveguide calibration standard set. The calibration set consists of a thru line, four longer lines, and two offset shorts, and is suitable for performing calibrations to 40 GHz. The standard version number in the upper right hand corner of the calibration set ("CPW 01" in this case) is used to keep track of design changes. Seven calibration sets are incorporated on each wafer. Each calibration set is assigned a number which is found directly below the version number. The structures on the lower right are experimental Line-Reflect-Match (LRM) calibration structures.

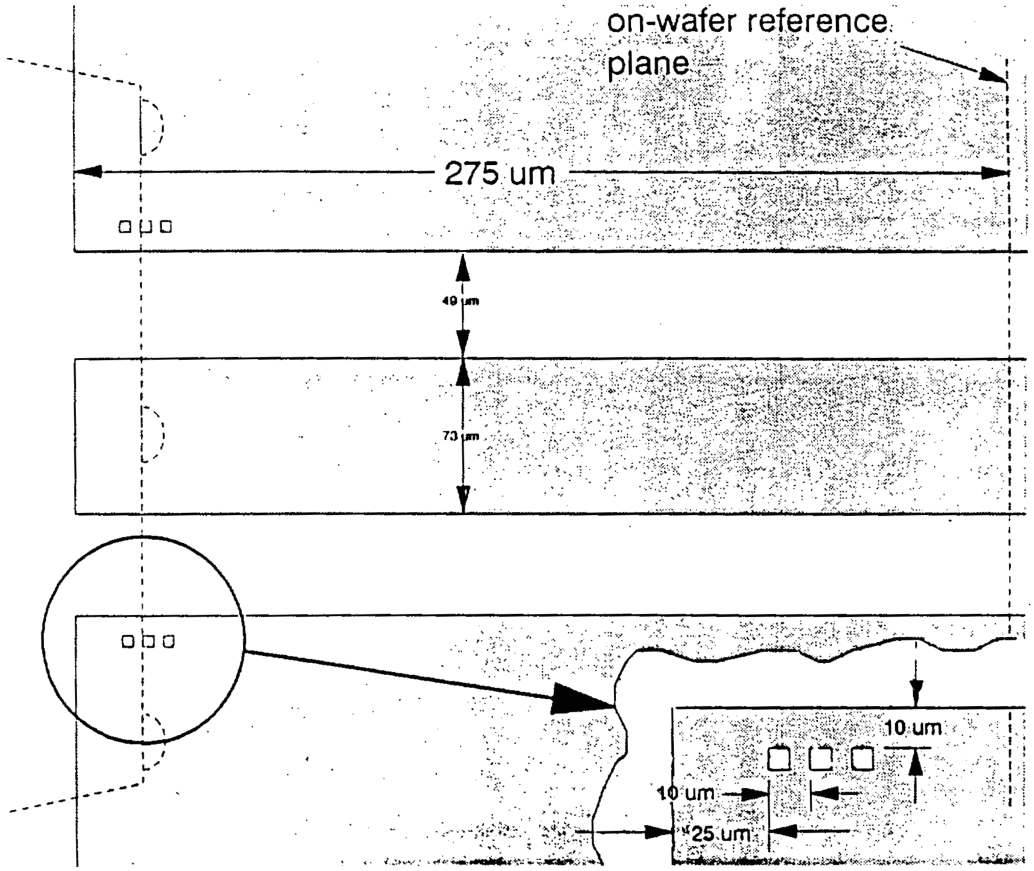


Figure 2. The probe tip-to-CPW launch structures are shown. The recommended probe tip position after alignment is shown in dashed lines. The three pairs of alignment marks have dimensions of 5 μm by 5 μm. Their positions relative to the metal edges are shown in the inset.

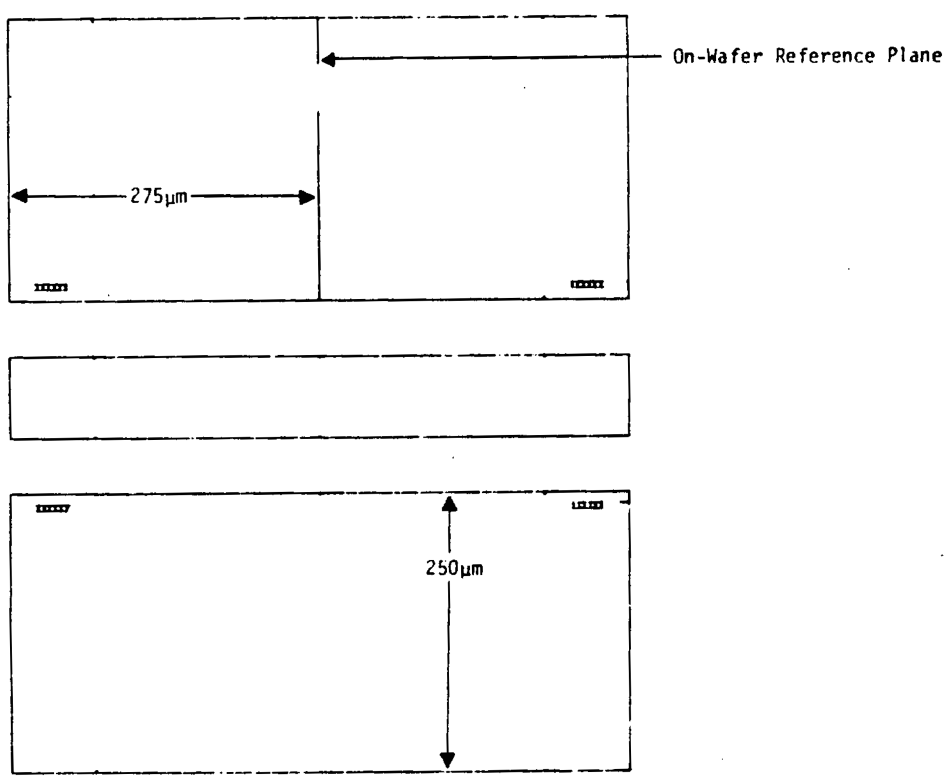


Figure 3. The thru line standard is shown. The on-wafer reference plane is placed exactly in the center of the thru line structure.

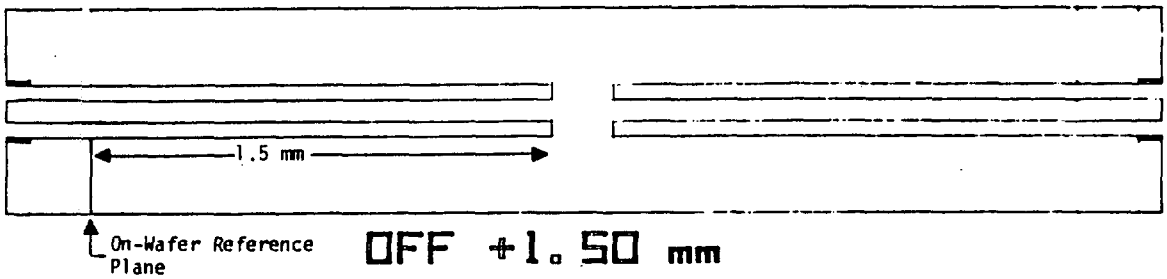


Figure 4. The +1.5 mm offset short is shown. The short is located at a distance of 1.5 mm after the on-wafer reference plane. The offset shorts are used as reflect standards in the TRL calibration procedure.

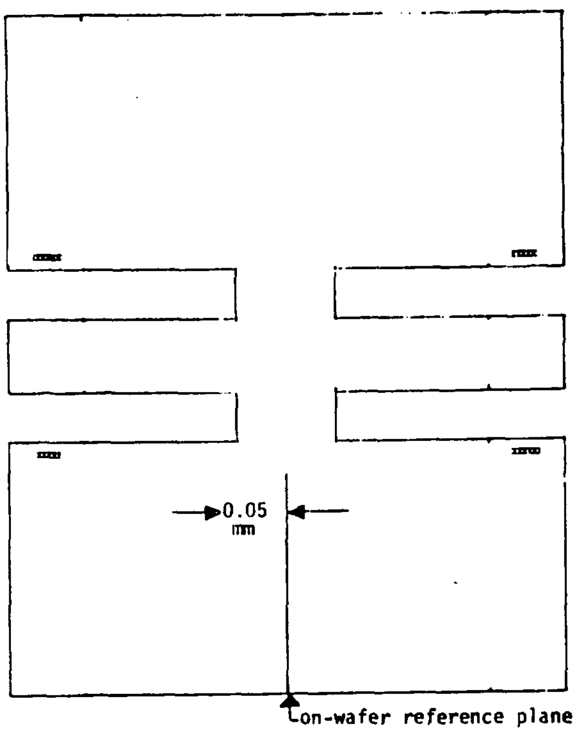


Figure 5. The -0.05 mm offset short is shown. The short is located at a position 0.05 mm before the on-wafer reference plane. The position of the short is negative because it lies between the probe tip and the on-wafer reference plane.

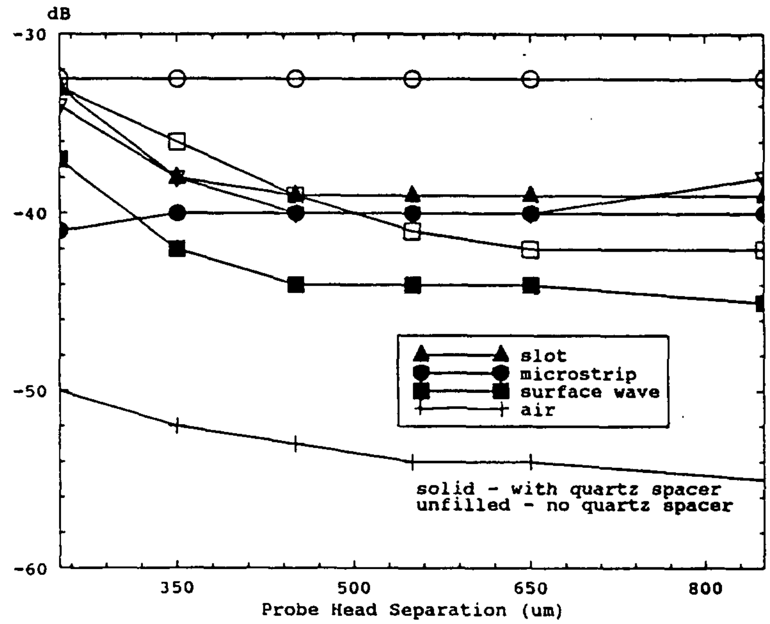


Figure 6. The worst case probe-to-probe coupling in various experimental configurations is plotted as a function of probe head separation. The probe head separation is defined in terms of the length of line which the probes contacted with our launch.

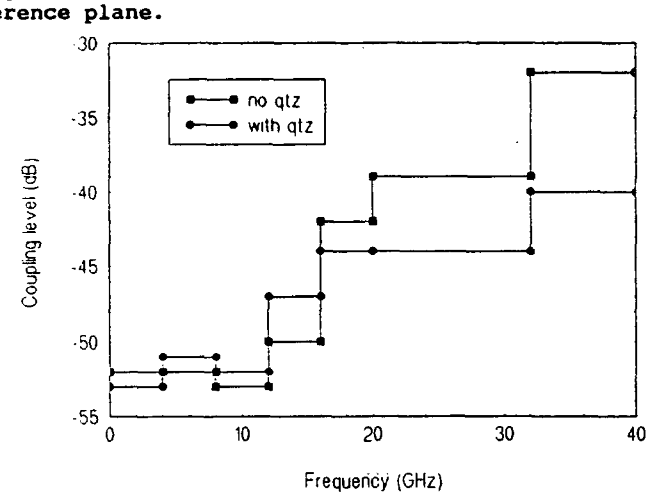
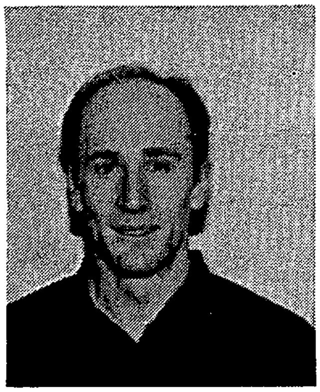


Figure 7. The worst case probe-to-probe coupling we measured in the experiments described here both with and without the quartz spacer for a probe head separation of 550 µm over various frequency bands.



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Kurt R. Phillips received his BSEE from the University of Colorado and is pursuing graduate studies in the design and fabrication of microwave circuits. Upon joining NIST, he worked in the development of calibration methodology on the six-port network analyzers. Presently, he is involved with the development of on-wafer S-parameter measurements.