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# A BROADBAND CPW-TO-MICROSTRIP MODES COUPLING TECHNIQUE

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**Abstract -** A broadband vertical transition from coplanar waveguide (CPW)-to-microstrip modes is presented. The transition has a double resonance and can be tuned for very wide-band operation. The CPW-to-microstrip modes coupling technique is useful for the vertical integration of multi-layer millimeter-wave circuits, packaging and antenna feeding networks. A vertical transition has been fabricated on 100 μm silicon substrate for operation at W-band frequencies and shows less than 0.3 dB of insertion loss and better than 12 dB of return loss from 75 to 110 GHz. A 94 GHz CPW-fed microstrip antenna showing a 10-dB bandwidth of about 30 % has been built using the same transition technique.

**Keywords** - wideband transition, multi-layer circuit, microstrip antenna, millimeter-wave circuits.

## I. Introduction

As the need for microwave and millimeter-wave circuits to become more compact grows, new techniques for integration have to be investigated. Many techniques have been developed that allow lines and components to be placed closer together in circuits with little or no degradation in performance [1]-[3]. Recently, the integration path has entered into the third dimension where multiple circuits are being integrated vertically to reduce the total space and cost of high frequency systems. At millimeter-wave frequencies, interconnects, transitions, and packaging techniques become more and more difficult because of the increased influence of discontinuities and substrate losses. One major concern when designing multi-layer circuits, especially at high frequencies such as W-band, is propagating the signal from one level to another with a minimal



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degradation in overall circuit performance. There are a number of different mechanisms that can cause circuit's performance to degrade. One cause is reflections from a mismatched transition. Reflected signals result in an overall loss of power, which is costly at high frequencies, and can also result in reduced or altered responses from individual components such as filters or amplifiers (which are normally designed to have a matched terminations at all ports). Another mechanism which also results in signal loss is radiation as the signal propagates vertically between the layers. This can be especially harmful to the overall system performance because this radiation, usually in the form of substrate modes, can result in unwanted coupling between many of the individual components in the system. Reduced isolation, decreased efficiency, and parasitic oscillations are some of the unwanted results of substrate mode coupling. Also, unwanted surface waves are more easily triggered into the substrate since the dielectric constant of standard Monolithic Microwave Integrated Circuit (MMIC) substrate is high ($\varepsilon_r$ = 11.7 for silicon and 12.9 for GaAs). Vertical transitions are therefore one of the key elements for building high-performance millimeter-wave circuits and modules. The two basic methods used for transferring high frequency signals from one side of the substrate to the other are physical contacts with via holes and electromagnetic coupling.

The first method involves physical contact between the transmission lines lying on the top and the bottom of the substrate. The energy is transferred through conduction currents that run along the conductors between the layers. This type of transition provides a DC path between the layers, it is relatively tolerant of fabrication misalignments, but it does require processing steps to etch and metallize via holes. This type of transition presents fairly broadband performance and can often be modeled using simple lumped element circuit simulators along with static field solvers.

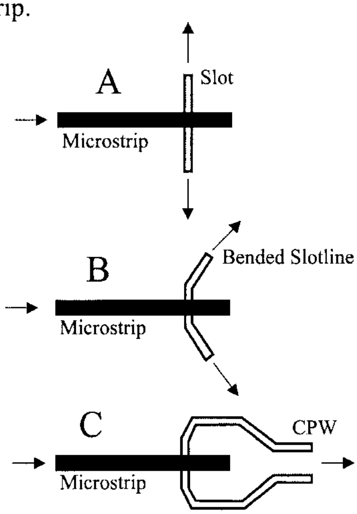
Electromagnetic coupling is the second form of coupling commonly used for vertical transitions. The energy is transferred by coupling the fields from one mode into the fields of the other. This method provides an inherent DC isolation between modes and requires no extra processing step such as via holes. However, this type of transition can be extremely sensitive to alignment errors during processing and can be difficult to model without the use of 2.5-D or 3-D field solvers. It also tends to produce lower bandwidths than those achieved with physical contact coupling. CPW-to-CPW [4]-[5] and more recently microstrip-to-microstrip [5] vertical transitions based on electromagnetic coupling have been reported in the literature.

Microwave and millimeter wave circuits and modules are usually based on planar technologies using microstrip or CPW topologies since they can provide a compact, light-weight and low loss transmission medium. CPW or microstrip transmission line is prefered depending on the specifications of the circuit. In a complete millimeter-wave systems the use of both topologies offers more freedom for the design. Microstrip-to-CPW transitions are therefore needed in such systems. Planar microstrip-to-CPW transition has been published by Burke *et al.* in [6] and more recently by some of the authors [7].

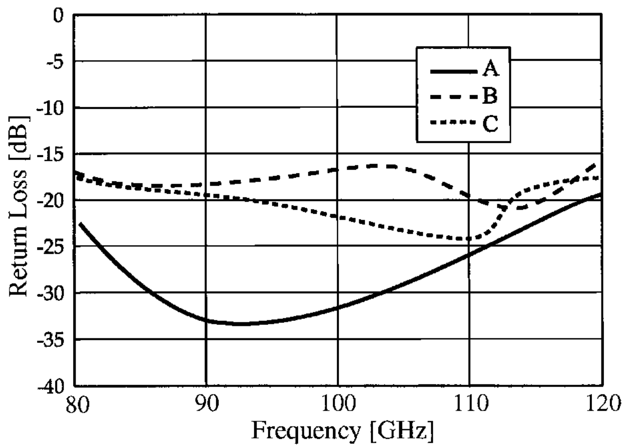
In this paper, experimental and simulation results for a broadband the microstrip-to-CPW modes coupling technique are presented. The electromagnetic coupling technique is described in Section II and successful designs of a wideband microstrip-to-CPW vertical transition and CPW-fed microstrip antenna are shown in Section III and IV, respectively. The experimental results are finally summarized in Section V.

## II. Microstrip to Slotline Mode Coupling

In a microstrip-to-slotline power divider energy is coupled into the slotline and allowed to propagate in both directions. This element has a single resonance that is defined by the microstrip open stub length. It is useful to note that the CPW transmission line is actually coplanar slotlines with a 180° phase difference between the slots. If the individual slotlines from the power divider are bent around and brought together, they naturally form CPW with the 180° phase shift coming from the spatial orientation of the lines. Assuming the bending of the lines is gradual, there are no reflections as the slotlines form the CPW and the structure maintains the original resonance. A diagram and simulated return loss for the transition is shown in Fig. 1. Simulated results show the negligible effects on the transition return loss of the gradual bending of slotlines into CPW. The loss in the passband is due to an impedance mismatch and can be most easily controlled by the width of the slotline underneath the microstrip.




(a)




(b)

**Fig. 1.** Vertical microstrip-to-slotline transition: (a) conversion of slotline into CPW mode, (b) simulated return loss for the three cases.

It was found that a second resonance could be introduced to this type of transition to increase the bandwidth significantly. Actually, while the gradual bending of the lines provides a wide bandwidth, it would take up a great deal of space, something extremely valuable in microwave circuit design. In the transition previously reported [8] the slotline sections were not slowly bent into the CPW line. Instead they were bent at 90° and chamfered a short distance away from where the microstrip line crosses over the slotline. The strong discontinuity introduces a second resonance into the transfer function of the power divider. The location of the second resonance is controlled by the distance "*d*" between chamfers as indicated in Fig. 2. With this added degree of freedom the response can be adjusted for a minimum return loss at the center frequency (i.e. a Butterworth response) or it can be shifted to obtain a two-pole equal-ripple response with greater bandwidth but at the price of increased reflection loss (a Chebyshev response). By adjusting the geometry, the effective turns ratio for the impedance transformer of the coupling is changed and can be optimized for improved return loss independent of the location of the poles which are controlled by the distance "*d*".

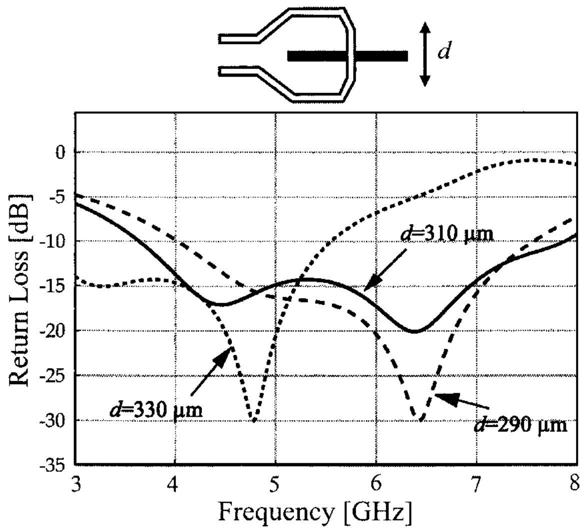


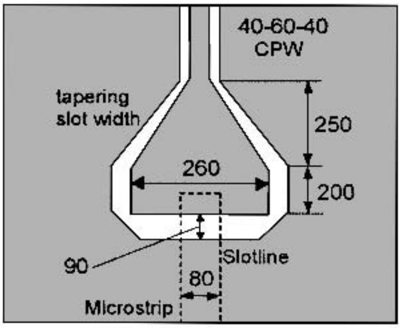

**Fig. 2.** Simulated return loss for the transition showing the control of the pole locations versus the distance "*d*".

## III. Vertical Microstrip-to-CPW Transition

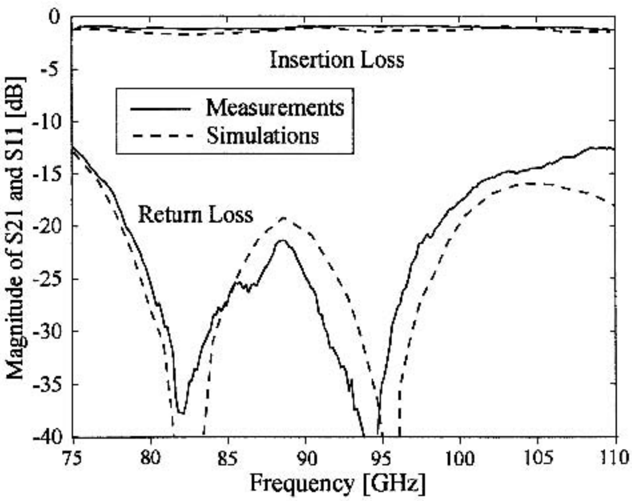
The transition is uniplanar and is simple to fabricate as it does not rely on via holes or micromachining techniques. The design begins with a microstrip to slotline power divider, with the slotline being integrated in the ground plane of the microstrip line. This is essentially two parallel slotlines acting as a single CPW transmission line. If the symmetry is not disturbed then the fields will still be of equal amplitude, but there is now the 180° shift phase required for CPW propagation due to the spatial orientation of the slots. The slotline width under the microstrip section was chosen so that the parallel load presented a match to the microstrip input line. While a 50 Ω CPW line can be formed using this slot width it is often not optimum for a given application. The width of the slotline sections can be changed gradually as they taper together to form the CPW so that the desired aspect ratio is achieved once the 50 Ω CPW output line is formed as explained in Section II.

The transition was designed for fabrication on a 100 μm high-ρ silicon wafer. The conductor patterns were evaporated onto the substrate with a thickness of 1 μm (approximately 3 skin depths at W-band). The main dimensions of the CPW-to-microstrip transition are: 60 and 40 μm for the central conductor and slot width of the CPW line, 80 μm width for the microstrip line and 90 μm for the slotline crossing the microstrip line at the opposite side of the silicon wafer. All of the transition dimensions are given in Fig. 3a. The transition was done using a back-to-back configuration and measured from the CPW inputs using an HP-8510 network analyzer. The system was calibrated on-wafer using TRL standards which were fabricated with the transitions.

Fig. 3 shows the measured insertion and return losses for the built vertical transition. The total insertion loss is about 1 dB and the return loss always below 12 dB over the whole frequency range from 75-110 GHz. After de-embedding the CPW and microstrip lines losses, it results an insertion loss of about 0.25 dB for one vertical transition. Very good agreement between measurements and simulations run with HP-EEsof's Momentum software [9] is also observed.




(a)




(b)

**Fig. 3.** Transition dimensions, all dimensions are in microns (a), simulated and measured return and insertion losses for a vertical microstrip-to-CPW transition built on high resistivity silicon wafer of 100 μm thick.

A concern for designing vertical transitions is alignment, and electromagnetic coupling designs are often significantly more sensitive than physically coupled ones. Numerical simulations have been run for evaluating the impact of misalignment on the transition behavior. Misalignments versus *x* and *y* axes of up to 20 μm, which is much greater than would be expected from current fabrication processes, have been considered. Fig. 4 shows that even for misalignment as high as 20 μm the change of the return loss for the transition is negligible. Fig. 5 presents the measured insertion and return losses for identical vertical transitions built on three seperated wafers. These experimental results demonstrate the very high reliability of the transition behavior process to process.

One advantage this transition has over other reported vertical transitions is the simplicity of fabrication. There are no vias and it requires only two masking layers, one to define the microstrip line and a second on the opposite layer to define the slots.

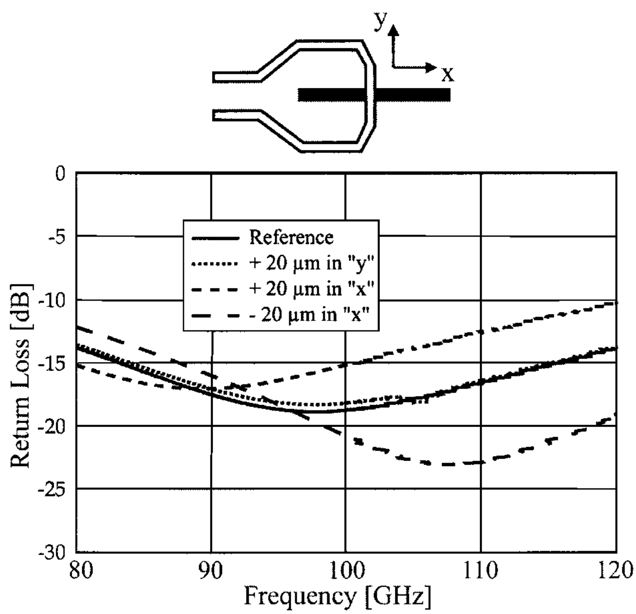



**Fig. 4**. Simulated return loss for vertical microstrip-to-CPW transition versus misalignments.

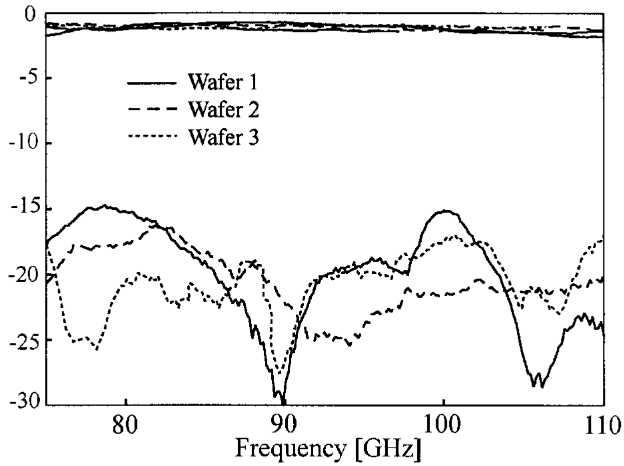



**Fig. 5.** Insertion and return losses for vertical microstrip-to-CPW transitions measured on three different wafers.

## IV. Wideband CPW-fed Microstrip Antenna

The transfer of energy from CPW-to-microstrip modes has been presented in previous section. A natural extension is the use of the same approach for feeding microstrip patch antenna with CPW line. The microstrip antenna is a very good common element in telecommunication and radar applications since it provides a wide variety of designs, can be planar or conformal, and can be fed using many different methods [10], [11]. It is also low-cost, compact and suitable for antenna array designs. At millimeter-wave frequencies, many limitations have to be overcome in order to design high-performance microstrip antennas on silicon or GaAs substrates.

The high dielectric constant of the substrates used allows for surface waves to be easily triggered in the substrate. A recent solution is the use of micromachining fabrication techniques to artificially remove the substrate below the antenna and therefore locally synthesize a low dielectric constant region around the antenna. This technique has been successfully applied by drilling closely spaced holes [12] or by etching an air cavity around and beneath the microstrip antenna [13], [14].

The possibility to feed the microstrip antenna through an aperture cut into its ground plane is another interesting characteristic of it. The electromagnetic coupling between a feed line and the patch antenna presents numerous advantages: no soldering points, weak parasitic radiation, greater radiation pattern symmetry, etc. To date, the primary source of an aperture-coupled microstrip antenna has usually been a microstrip line located below the ground plane [14]-[16]. Recently, the coplanar waveguide appeared as an alternative solution for feeding microstrip antennas [17]-[21].

CPW-fed aperture-coupled microstrip antenna is composed of two wafers: the top one supporting the metallic patch and the bottom silicon wafer on which the CPW feed line and coupled slotline are implemented. In this structure the metallic plane is used both as a conducting plane for the CPW line and a reflector plane for the radiating element. The two wafers are aligned and bonded together.

While the impedance bandwidth of a patch antenna is usually limited to about 5-10 % [14], it is possible to use the CPW structure to introduce a second resonance into the system in the same manner as previously described for the microstrip. The MoM simulations (HFSS and HP-EESof's Momentum Software) that were done show that the same type of resonance as in the transition can be introduced, with the location of the resonance having the same dependence on the length of the slotline section and the overall return loss level being a function of the width of this section. A slotline section was centered underneath the patch and was folded to form the CPW input line. The slotline corners (and their spacings) used to form the CPW line introduce a second resonance into the system. This second resonance can be adjusted by altering the degree of chamfering at the corners of the slotline bends and the spacings between them, as described in Section II. This allows the input return loss to be adjusted to the desired response.

Using this procedure a microstrip patch antenna was designed for wide bandwidth operation centered at 94 GHz. The second resonance was adjusted to be near 105 GHz and allowed the overall bandwidth for the antenna (as measured from the 10-dB return loss point) to exceed 25 %. The antenna and feeding line dimensions are given in Fig. 6. Fig. 7 represents the simulated and measured input impedance of two similar CPW-fed aperture-coupled microstrip antennas, labeled circuits 1 and 2. A good agreement is obtained between simulations and measurements. The measured return loss is –27 dB at 94 GHz for a 10-dB bandwidth greater than 25 %. Typical radiation patterns for microstrip antenna have been measured with a front-to-back ratio lower than –10 dB over the whole patch bandwidth. While this antenna was made from two silicon wafers, the design procedure would allow for the same results using a single dielectric wafer with two metal layers (the CPW side and the patch).

Another benefit of this design technique is that the resulting response is not critically dependent upon manufacturing tolerances, as discussed before. Actually, the same center frequency at 94 GHz has been measured for the two CPW-fed microstrip antennas labeled circuits 1 and 2 in Fig. 7. This is in great contrast to the alignment analysis of the slot-coupled patch antenna shown in [14]. Effectively, non-negligible frequency shifts of the measured input impedance for two similar microstrip-fed aperture-coupled microstrip antennas had been clearly observed. The frequency shifts between them are attributed to the fabrication accuracy, and more particularly, to the alignment technique precision used to stack the feed and antenna wafers together. Actually, the accuracy of this bonding technique is around 5-10 μm. For example, if we consider a hypothetical misalignment of 10 μm between the two wafers following the $x$-axis in the positive direction, in this case the microstrip matching stub length is $L_{st}$ = 260 μm instead of 250 μm as designed [14]. The input impedance of this modified design has been simulated and compared to the simulations results obtained for the "original" design. The simulations predict a frequency shift of the input impedance of approximately 3 GHz due to a 10 μm misalignment between the two wafers. This is in agreement with the experimental results presented in [14].

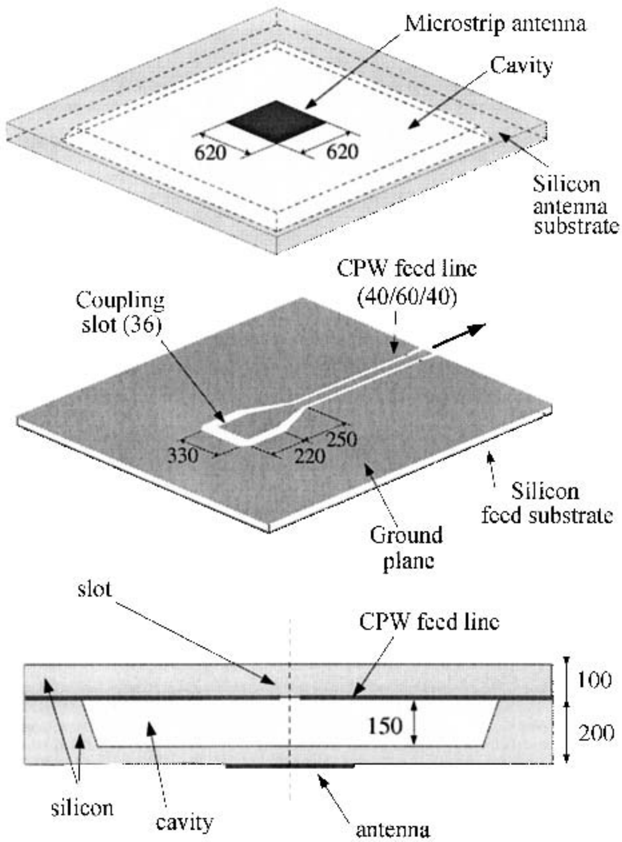



**Fig. 6.** Perspective view (a) and cross-section (b) of the CPW-fed aperture-coupled micromachined microstrip antenna. All dimensions are in microns.

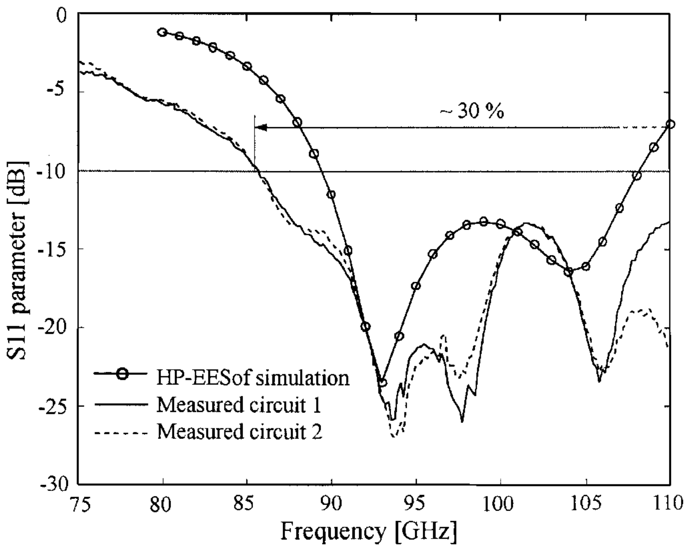



**Fig. 7.** Measured and simulated (HP-EESof's Momentum software) input impedance of the CPW-fed aperture-coupled micromachined microstrip antenna.

## V. Conclusion

A broadband vertical transition from coplanar waveguide-to-microstrip modes has been presented. A broadband single layer vertical transition from CPW to Microstrip line has been developed that requires no via-holes, micromachining, or air bridges. It has very low insertion loss (< 0.3 dB) and good return loss (> 12 dB) across a wide bandwidth (75 - 100 GHz). It was developed for use in millimeter-wave multilayer circuits and for packaging the requirements between CPW modules and microstrip carriers common with today's integrated circuits. Based on the same coupling technique a CPW-fed aperture-coupled micromachined microstrip antenna at W-band frequency has been designed. This microstrip-type antenna has an excellent a 10-dB bandwidth (30 %), good patterns and high-efficiency performance, and is compatible with silicon or GaAs MMIC technology. It is a very efficient solution to the vertical integration of antenna arrays at millimeter-wave frequencies.

## VI. Acknowledgements

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