OCTAVE-BANDWIDTH HIGH-DIRECTIVITY MICROSTRIP CODIRECTIONAL COUPLERS

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Abstract — **It is a well-known problem with microstrip backward-wave couplers that directivity suffers due to the differing phase velocities of the even- and odd-mode waves. A fully-planar alternative is the forward-wave, or *codirectional*-coupler, but these structures have not yet been widely accepted, in part because they are complex and tedious to design. Here, we offer a simple quarter-arc geometry for loosely-coupled microstrip couplers with high-directivity that can be very quickly modeled and prototyped. A design example of a 50-110 GHz 12 dB coupler is shown in Figure 1. Measurements indicate that the coupler has better than 20 dB directivity over the full octave bandwidth.**

I. INTRODUCTION

A common passive element needed in microwave and millimeter-wave systems is the directional coupler. The *simplest* microstrip solution is the backward-wave coupler formed by a quarter-wavelength section of edge-coupled transmission lines. It is commonly known, however, that microstrip implementations of this coupler suffer from poor directivity as a result of the differing even- and odd-mode phase velocities. This is why commercial couplers of this type are almost exclusively built in stripline. Unfortunately, stripline circuits are more difficult to integrate with microstrip or CPW MMIC-based modules. The problem of phase-velocity compensation in microstrip couplers has been studied by many researchers, and a number of techniques have been proposed [1]. For example, some improvement can be achieved with lumped capacitors between the lines at both ends of the coupler, or by meandering the gap between the coupled lines (the so-called "wiggly" or "serpentine" couplers) to slow down the odd-mode without significantly affecting the even-mode [1]. The former option requires discrete parts to be soldered into place (since capacitors are not usually available in a ceramic or soft-board manufacturing process), and the latter method really only works well when the lines are close together, i.e. when the component has tight coupling.

For loose couplers, an easier, fully-planar alternative is to use a codirectional coupler. In the common backward-wave coupler, one uses the fact that the even- and odd-mode waves have differing impedances, but it is assumed (incorrectly, as described above) that their phase velocities are equal. Therefore, when the two modes reach the end of the coupled-line section, which is usually terminated with 50 Ω loads, the higher-impedance even-mode reflects with 180° phase shift and the lower-impedance odd-mode reflects with no phase inversion. The two modes then add constructively on the coupled-port in the reverse-direction, launching the coupled wave backward. In a codirectional coupler, however, one uses the differing phase velocities to build up a coupled-wave in the forward direction, and the task is simply to ensure that no reflection of the even- and odd-modes occur which would launch a backward wave and degrade the directivity. It is possible to match both modes, even though they have different impedances, by gradually tapering the exits from the coupled-line section at both ends.

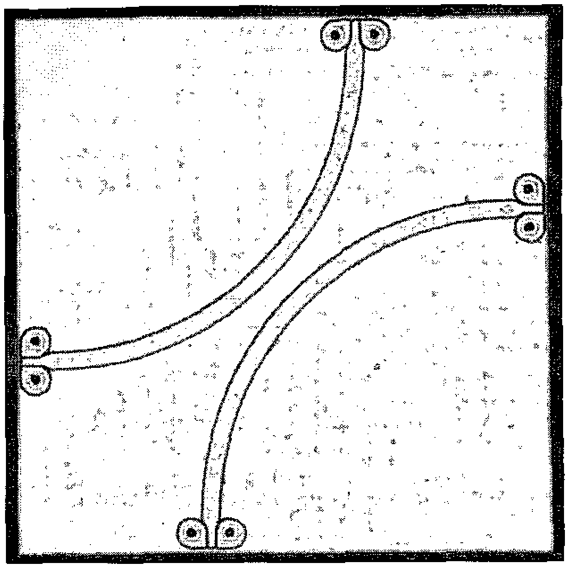

Fig. 1. A 50-110 GHz arc-coupler. Alumina substrate dimensions are 4.6 x 4.6 x 0.13 mm.

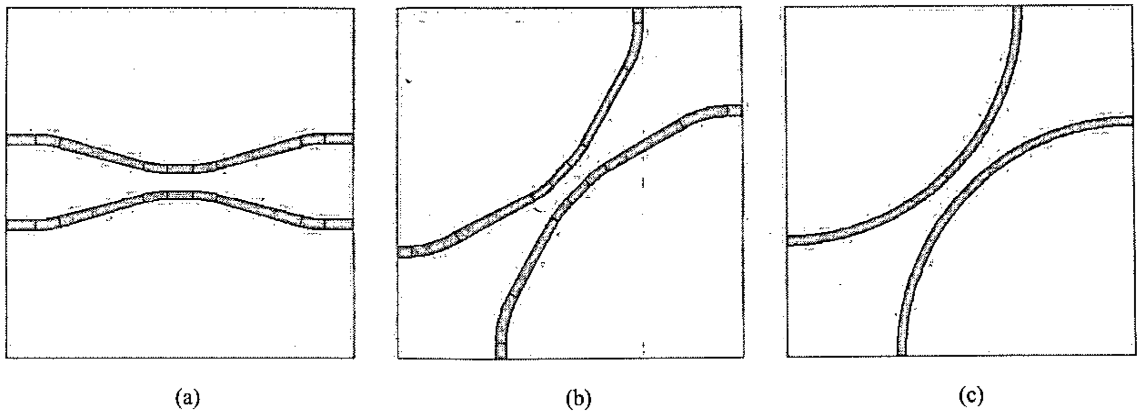

Fig. 2. Evolution of the arc-coupler topology: (a) standard codirectional coupler, (b) rotated codirectional coupler, and (c) arc-coupler geometry.

II. Evolution of the Arc-Coupler Geometry

Charged with the task of designing a millimeter-wave coupler for a MMIC-based application, the authors began with the basic topology of a codirectional coupler shown in Figure 2a. There are a large number of parameters that all play a role in determining the coupling factor, input match, and directivity of this design. The importance of the tapered end-sections should not be underestimated, since they are precisely what makes this codirectional, rather than the backward-wave variety, and will directly influence the directivity of the final circuit. The taper must be long enough to provide a good match to both modes at the lowest operating frequency and should separate the feedlines by a great enough distance to completely decouple the transmission lines. Radiusing the bends is also critical to matching both modes, and cannot be done too sharply. Unfortunately, it also makes analyzing the overall structure more difficult since the gradual turn will effectively lengthen the coupled-line section, changing the coupling factor and operating frequencies. One inevitably ends up having to optimize a large number of design parameters in a numerical simulator, which is both tedious and time-consuming.

A practical detail that one should also consider is that a multi-chip system in which this coupler is used will be more difficult to layout if any two of the ports come out on the same edge of the chip. It is more convenient if each of the four ports lies on a separate side. Thus, it is useful to rotate the whole structure 45° as shown in Figure 2b. The critical dimensions are exactly the same, so the initial simulation need not be revised, but having drawn this picture the authors noticed how much the two metal traces resembled quarter-arcs of circular rings. Out of sheer curiosity, we tried simulating the simpler arc-coupler structure shown in Figure 2c. This is of course much easier to optimize as it only has two parameters to deal with: the radius of the arcs and the minimum separation between them (the width of the trace was fixed to that of a 50 Ω microstrip line). The structure is so much simpler, in fact, that our first best-guess dimensions resulted in better performance (in terms of directivity and input match) than the optimized version of the coupler shown in Figures 2a-b.

III. A 50-110 GHz Design Example

Taking advantage of this serendipitous discovery, the authors quickly prototyped a broad 50-110 GHz coupler which was needed for a MMIC-based Vector Network Analyzer. Theoretically, the coupling of a codirectional design will vary as

$$s_{31} \approx -j \sin\left(\frac{\pi \Delta n_{eff} L}{c} f\right) \qquad (1)$$

$$\Delta n_{eff} = \sqrt{\varepsilon_{eff}^{even}} - \sqrt{\varepsilon_{eff}^{odd}} \qquad (2)$$

where L is the length of the coupled-line section, and Δn_{eff} is the difference between the square roots of the effective dielectric constants of the two modes [2]. So, an octave-band coupler like this one would normally have about 3 dB coupling variation. This is perfectly tolerable in a VNA since the precise coupling is not critical and will be taken out in the usual calibration of the instrument. Further, the stronger coupling occurs at the high end of the band, and may help to offset the usual roll-off that amplifiers and other components tend to experience at higher frequencies. For this project, it was decided to

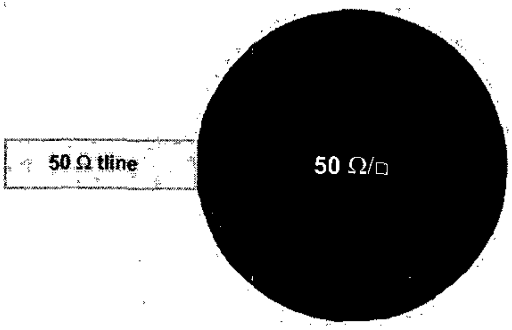

Fig. 3. *Diagram of the dot-termination. The diameter of the* thin-film disc was 800 μm, setting a lower frequency limit of about 30 GHz.

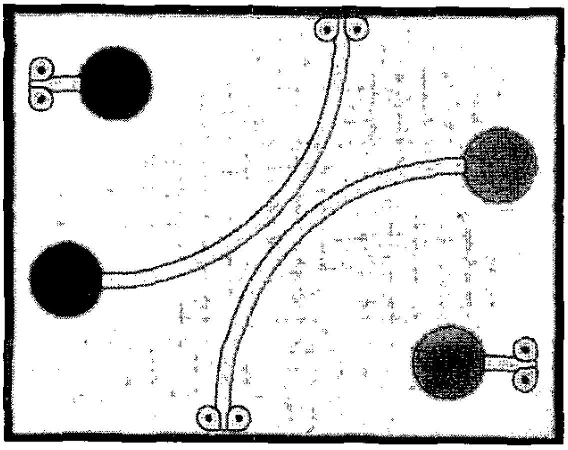

Fig. 4. Photograph of the test substrate for measuring dot terminations and forward-coupling of the 50-110 GHz coupler.

design for a nominal 9-12 dB coupling factor.

The simple coupler geometry shown in Figure 2c was modeled with Ansoft's High-Frequency Structure Simulator (HFSS). The simulation predicted that the arc-geometry would have slightly more variation in coupling factor over the octave bandwidth than the 3 dB that was calculated for a straight codirectional coupler, but the directivity remained very good. Final dimensions for the line spacing and radius were selected after only a few iterations.

IV. TEST RESULTS

In order to verify the design, it was necessary to make test pieces which had 50 Ω terminations on two of the four ports. Since the quality of the termination will limit the measurable directivity, it was important to design a

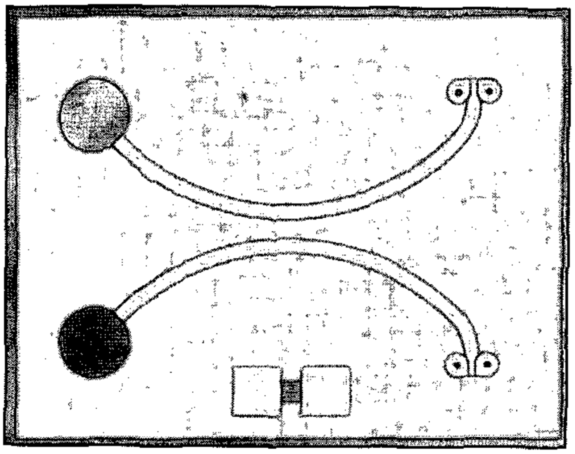

Fig. 5. Photograph of the test substrate for measuring isolation of the 50-110 GHz coupler.

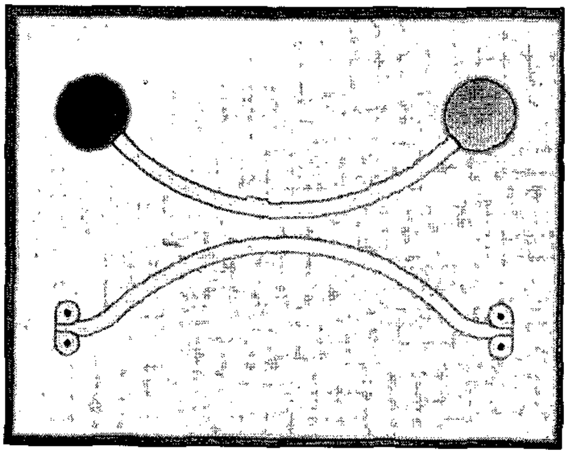

Fig. 6. Photograph of the test substrate for measuring insertion loss of the 50-110 GHz coupler.

load that would have good return loss over the full bandwidth of the coupler. A *dot-termination* was used, which consists simply of a disc of thin-film material with sheet-resistance equal to 50 Ω/□ [3]. This termination has a lower-frequency limit set by the diameter of the disc, and upper-frequency limited only by moding of the microstrip line. A sketch of the dot termination used for this project is shown in Figure 3. The dot diameter used was 800 μm which simulations predicted would have excellent return loss above about 30 GHz.

Three test pieces were fabricated, and are shown in Figures 4-6. The first was used to measure forward-coupling, the second for isolation, and the third for insertion loss. Standalone terminations were included on the piece in Figure 4 for verifying the dot's performance.

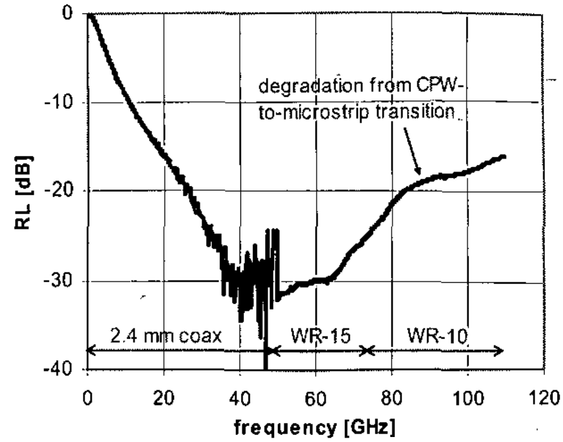

Fig. 7. Return loss of the 800µm dot-termination measured in three VNA bands. The degredation above 70 GHz is believed to be due to the CPW-microstrop transition rather than the termination itself.

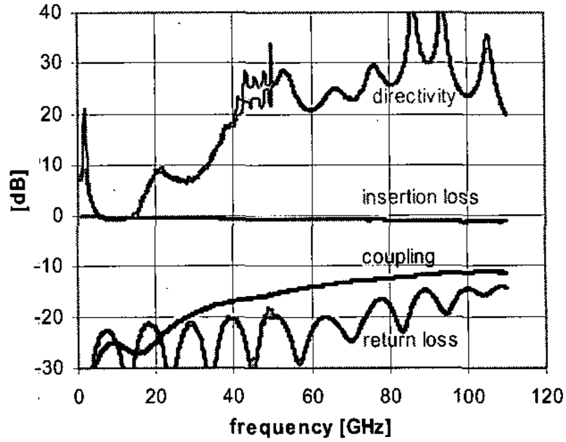

Fig. 8. Measured coupler performance.

All test pieces as well as the final coupler (Figure 1) were fabricated by American Technical Ceramics on 127-µm thick Alumina substrates.

Measurements were performed with an HP 8510C Vector Network Analyzer. Above 50 GHz, external VNA extensions from Oleson Microwave Labs were used to test the circuits in WR-15 and WR-10 bands. The 1-port measurement of the dot-termination is shown in Figure 7. The return loss is better than 25 dB from 30 to 75 GHz. It degrades to 16 dB by 110 GHz, but this is consistent with the expected performance of the microstrip-to-CPW transition that was necessary to land the wafer probes, and is not an indication of the dot's high-frequency return loss. Fortunately, the transition is not present on the terminated ports of the test couplers, and will not therefore limit the directivity that is measured. Based on simulation, the dots alone are believed to operate very well up to and beyond 110 GHz.

The measured performance of the coupler is plotted in Figure 8. The coupling factor was a bit lower than the simulation, but as expected, the maximum coupling occurred at 110 GHz, with a value of 11.2 dB. It fell to 12.8 dB at 75 GHz, and 15.4 dB at 50 GHz. Input return loss was at least 15 dB, and directivity was better than 20 dB across the full octave of bandwidth. Maximum insertion loss was 1.1 dB at 110 GHz. This data was corrected for a small error in the transmission line impedance by renormalizing the s-parameters to 48 Ω, but this amounted to less than a 2 dB correction in the directivity and input match.

V. Conclusion

A new geometry for microstrip codirectional couplers has been presented. The structure is much simpler to design and optimize than conventional codirectional varieties, and has much higher directivity than backward-wave microstrip couplers. An octave-bandwidth millimeter-wave design was fabricated, and test results show 20 dB directivity from 50-110 GHz.

Acknowledgement

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