K/Ka-Band Coplanar Waveguide Directional Couplers Using a Three-Metal-Level MMIC Process

Tacar Gokdemir, *Member, IEEE,* I. D. Robertson, *Member, IEEE,* Q. H. Wang, and A. A. Rezazadeh, *Member, IEEE*

***Abstract*—Two novel types of coupled line structures have been realized on GaAs monolithic microwave integrated circuits to obtain 90° couplers operating at a center frequency of 24 GHz. Both of the couplers are made up of either two or three conductive layers to improve the coupling. The aim is to achieve compact couplers with smaller aspect ratios and to decrease the losses due to field crowding on the edges. Both couplers have achieved good matching and coupling. The simulation is carried out on the electromagnetic simulator *em* (a trademark of Sonnet Software Inc.).**

I. Introduction

Coplanar waveguide transmission line couplers were first investigated about two decades ago. On MMIC's they are commonly used in balanced amplifiers, phase shifters, and mixers for power splitting or combining. The first CPW coupler designed by Wen achieved 10-dB coupling and was realized by placing two transmission lines very close to each other [1], [2]. This kind of edge coupling requires narrow gaps between two transmission lines and 3-dB coupling cannot be achieved because of the limit on the physical size of this gap. The new generation of multilayer couplers is the solution for the physical limitations on gap size and the losses due to field crowding on these edges. This letter describes the design of two 3-dB couplers that incorporate multilayer structures to reduce the aspect ratio of the circuit. To obtain tight coupling and to improve losses, a combination of both edge coupling and offset broadside coupling has been used. The cross sections of both couplers are illustrated in Fig. 1. The even and odd mode characteristic impedances of the couplers were not theoretically evaluated using conformal mapping due to the complex arrangement of the geometry. Instead, electromagnetic simulation was used to find the required horizontal dimensions.

II. Fabrication

The structures presented here were fabricated at King's College London. The metal layers are all 1 μm thick and are separated by 2-μm-thick dielectric layers of polymide with a relative dielectric constant of 3.4. The semi-insulating GaAs substrate is 400 μm thick and has a relative dielectric constant of 12.85. The interconnections and plating up between layers are performed through suitable dielectric vias, which are plasma etched. The metal layers are thermally deposited by Genivac evaporation. The Hitachi PIQ-13 polymide films are formed by spin coating at 3000 rpm for 30 seconds and cured at 325°C to form high-quality films.

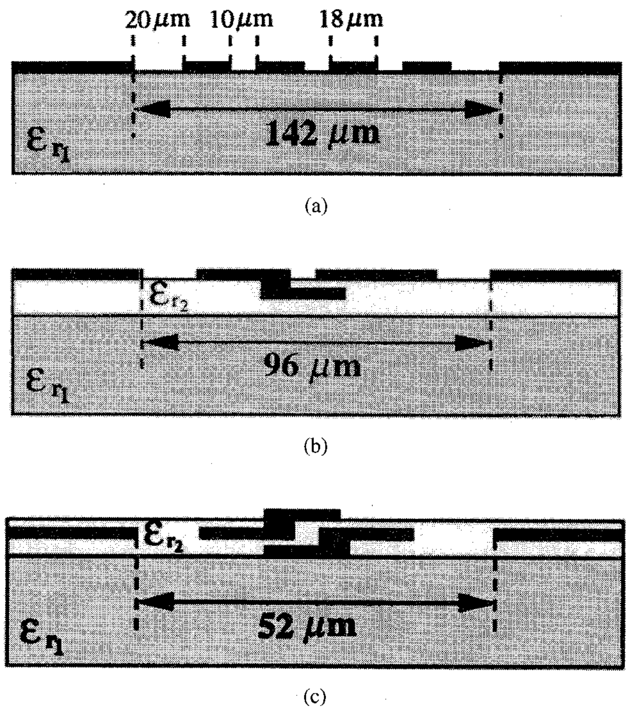

Fig. 1. Cross sections of couplers (not to scale). (a) Typical interdigitated CPW coupler. (b) Coupler 1. (c) Coupler 2.

III. Coupler 1

This coupler is like the one reported by Gillick *et al.* [3], but as there are more layers it has been possible to modify the geometry for improved performance. Coupling is increased by having a combination of edge and broadside-coupling and the additional edge-coupling compensates for the reduction in the broadside coupling due to the offset process. The insertion loss of the lower metal is lowered significantly by plating up the lower metal with the upper bulk metal through a dielectric via [4], [5]. The conductive tracks of

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The authors are with the Communication Research Group, Department of Electronic and Electrical Engineering, King's College, University of London, Strand, London WC2R 2LS, U.K.

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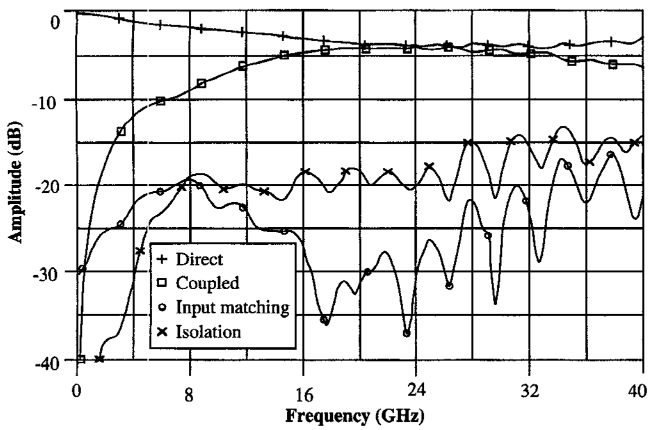
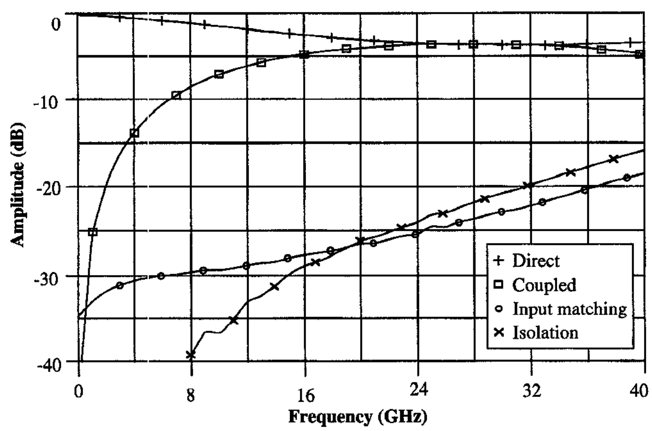


(a)



(b)

Fig. 2. Coupling, input matching and isolation characteristics of coupler 1. (a) Measured. (b) Simulated.

the coupler are much wider than those used for interdigitated couplers and are less sensitive to process variations [6], [7]. Simulations on *em* were performed on 100-μm-long subsections and included all the various dielectric layers. The simulated sections were then cascaded on Touchstone^{TM} to obtain the overall response. Between each port and the coupled line section an underpass connects the two coplanar waveguide grounds planes. These underpass connections are necessary to avoid propagation of unwanted modes and to keep the potential equal on separate grounds. The quarter wavelength coupled line at center frequency 24 GHz is 1.2 mm and the chip size is 1.79 × 0.65 mm. The conductors widths are 26 and 14 μm and the overlap is 4 μm. The separation is 10 μm. The simulated and resultant measured performance are shown in Fig. 2. The direct and coupled power responses show an equal power splitting with center frequency 24 GHz. However, when compared with the simulated data it can be seen that the measured response is slightly down shifted from the center frequency. Over the frequency range from 14–36 GHz the amplitude balance is within ±0.2 dB. The measured insertion loss is less than 1 dB at 24 GHz and almost identical to the simulated response. The input matching is good and it is below 15 dB. Isolation is better than 14 dB. The phase balance is within ±4° from 12–36 GHz as shown in Fig. 4 and very similar to the simulated one. The current distribution obtained from the *em* simulator shows that the main coupling is due to the offset broadside coupling between the top and bottom metal layers. Further examination has shown that the current concentration along the coupling edges on the top layer is reduced giving less field crowding and therefore resulting in a less lossy coupler. To calculate the ratio of guided wavelength ($\lambda_{even}/\lambda_{odd}$) Touchstone CAD package is used to fit a model to obtain the related parameters. The calculated ratio is 0.918.

IV. Coupler 2

The second coupler uses three conductive layers and the interconnections between conductors are made through a suitable dielectric via [8]. The main advantage of this novel structure is that it is very compact. The width between the ground planes on either side of the signal lines is half that of coupler 1. Therefore, the aspect ratio is even smaller. As well as having edge coupling, there is also twice as much offset broadside coupling between the conductors. One potential disadvantage is that it may be slightly more lossy because the edge coupling is through polymide instead of being through air as in coupler 1. The quarter-wavelength coupled line at center frequency 24 GHz is 1.2 mm and the chip measures 1.74 × 0.59 mm. The conductors dimensions are 10 μm and the overlap is 2 μm. The gap size for edge coupling is 12 μm. The addition of the offset broadside coupling on the top and bottom layers reduced the width to half that of coupler 1. The underpass cross connections were again used to avoid the propagation of unwanted modes. Fig. 3 shows the simulated and the measured performance of the newly developed coupler. Coupling loss of 4.1±1 dB, return loss of better than 13 dB, and isolation below 11 dB have been obtained over the 12–36 GHz frequency band. When compared with the simulated it can be seen that the simulated insertion loss is lower because the 2.5-D planar *em* simulator does not take into consideration the z direction. The simulated isolation is very close to the measured one. However, input matching is worse than predicted. One should not forget that the main aim was to half the aspect ratio in this novel coupler, and this is achieved using very small widths. However, this results in a coupler that is very sensitive to process variations. Thus, a small deviation from the actual widths results in large changes in the case of input matching. Unequal phase velocities between the even and odd modes reduces the directivity, but this could be improved on a second design iteration. The phase balance is within ±10° from 12–32 GHz as shown in Fig. 4. The simulated phase is further evidence of this sensitivity. The current distribution obtained from the simulator is similar to coupler 1 except that the main coupling is due to the two offset broadside. The edge coupling is still present but not strong as the offset broadside coupling. Current concentration along the edges is less and the field is distributed between three metal layers instead of two metal layers as in coupler 1. This novel design is very compact when compared with the existing Lange and multilayer couplers, and although it is more lossy, this can be overcome by careful design and plating up the metal layers. The use of less lossy and/or thicker dielectric layers will further reduce the insertion

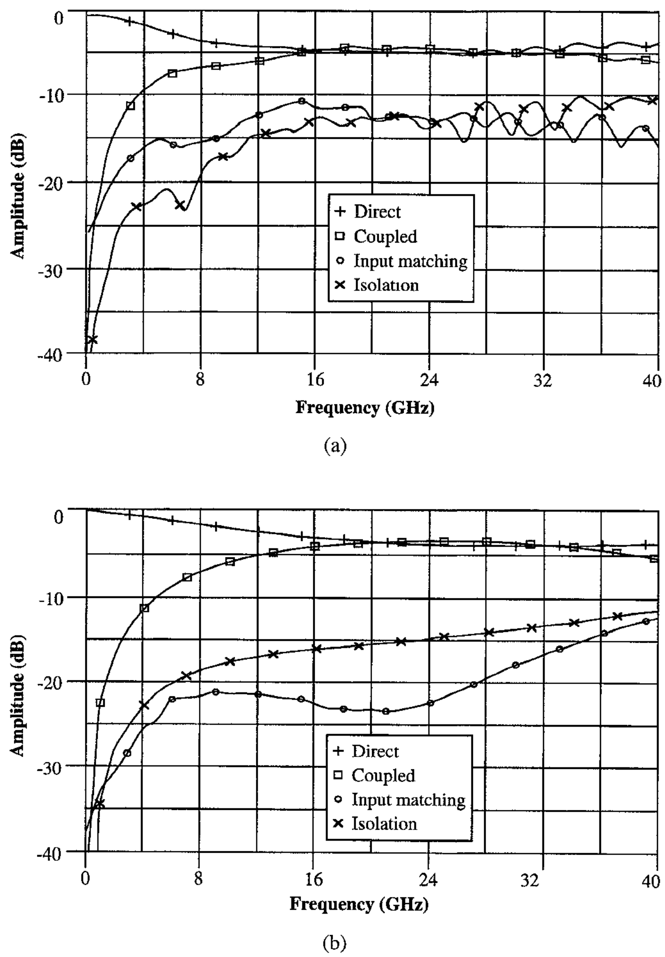


Fig. 3. Coupling, input matching, and isolation characteristics of coupler 2. (a) Measured. (b) Simulated.

loss. Similarly, fitting a model on Touchstone gives guided wavelength ratio of 0.962. Comparing this result with the previous one shows that electric field concentrates near the GaAs substrate and gives tighter coupling between the metal layers.

V. Conclusion

Coupler 1 has demonstrated a lower loss and improved performance compared to earlier multilayer monolithic couplers. This is a considerable achievement considering the experimental nature of the in-house multilayer technology.

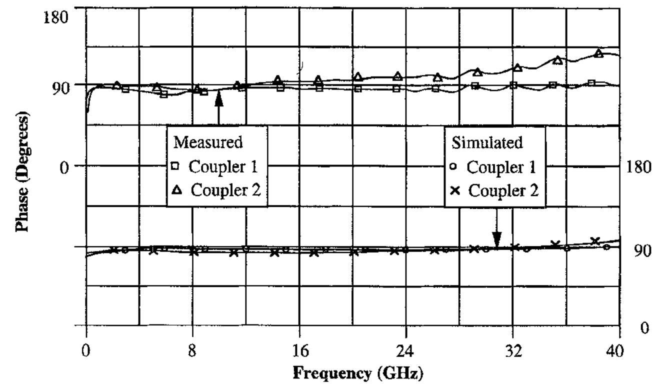


Fig. 4. Measured and simulated phase difference between outputs of coupler 1 and coupler 2.

Coupler 2 has somewhat higher losses, which is believed to be a result of higher field concentration within the polymide. However, coupler 2 requires half the chip area of coupler 1, and both these multilayer couplers require much less chip area than conventional interdigitated CPW couplers. Despite the complex 3-D nature of these new coupler geometries, "2.5-D" planar electromagnetic simulation is found to be a valuable design tool and both of the couplers are in close agreement with the simulated results.

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