A Comparative Study of Active and Passive GaAs Microwave Couplers

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Abstract — **This paper compares the design and performance of two types of wide band multi-octave MMIC couplers. An active coupler is based on pHEMT devices and fabricated in a GaAs foundry and a passive coupler uses coplanar waveguide (CPW) multilayer techniques. The multilayer couplers are fabricated on GaAs semi-insulating substrate and are reciprocal and directional. The active coupler design is adapted from the distributed amplifier circuit and is non-reciprocal.**

On-wafer RF measurements were carried out on the fabricated multilayer directional couplers and pHEMT based couplers. A multilayer quadrature directional coupler with coupling factor of 5dB and isolation of 10dB is realized over 10 to 35 GHz. A 180° coupler using pHEMT devices realized a coupling factor of 5dB and isolation of 26.5dB over 2 to 20GHz. For the first time the relative merits of the performance and implementation of these couplers are compared in view of their respective applications.

I. INTRODUCTION

Directional couplers are used in MMICs to realize balanced amplifiers, mixers and phase shifters. It is very important to select the correct technology, especially where the cost and circuit limitations are of prime importance. Active couplers can be designed and produced using a standard foundry process and can be made broadband by adapting the distributed amplifier circuit topology [1]. The distributed amplifier is inherently broadband and the modifications made to the circuit to produce a coupler increase the bandwidth and reduce the size of the circuit. In addition, this circuit topology shows low sensitivity to active device variations and does not depend on the control of the variation of line and gap dimensions for repeatability of performance. However, active couplers have limitations where linearity and power are the prime parameters. On other hand, passive couplers are reciprocal by their nature and can be used for many coupling applications provided the coupler's parameters can be maintained over a suitable bandwidth. Although various publications have reported the capability of passive or active couplers, there has not been a discussion concerning the direct comparison of the performance and implementation of these components. This paper addresses this comparison.

Coplanar waveguide structures facilitate grounding with low inductance, avoiding via holes through the substrate. By placing two transmission lines close to each other, Wen et al [2] achieved the first CPW based edge directional coupler with 10 dB coupling. To achieve a tighter coupling the two strips must be placed very close to each other. Achieving 3 dB coupling using edge coupling alone is not possible because of the limitation on the physical size of the gap between the two strips. Using multilayer techniques, both edge and offset coupling can be employed and this enables lower coupling factors to be achieved. In the design optimization of passive couplers one can achieve the gap size and also reduce the overall loss due to the current crowding at the edge of the conductors. The cross-sectional view of a multilayer directional coupler is shown in Fig. 1 with an overlap of 4 μm.

The directional couplers can also be realized using lumped elements and quasi-lumped element techniques [3], which, however, result in reduced operating bandwidth. Therefore, a distributed amplifier topology has been proposed [4] for the realization of a non-reciprocal coupler. Although this technique has some limitations in the application where a directional coupler would be used, the fact that it is broadband and can be easily implemented in MMIC form attracts RF designers.

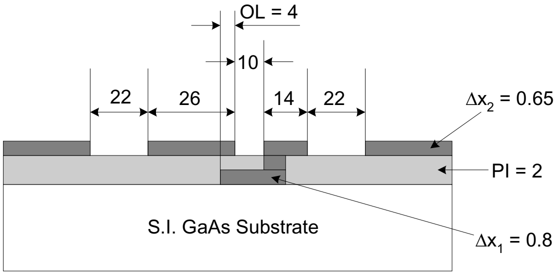

Fig. 1. Cross sectional view of a CPW multilayer coupler (all dimensions in μm)

It is apparent from the design methodology for the active and passive couplers that a fundamental difference exists between the way the coupling factor is set. The passive coupler requires the setting and control of the transmission line overlap dimension, whereas the active coupler requires a series gate capacitor to be determined for the appropriate coupling factor.

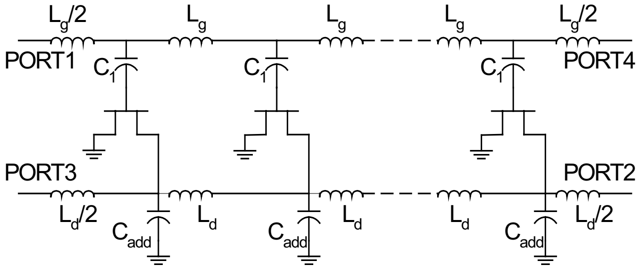

Fig. 2. Lumped element coupler circuit for pHEMT coupler

II. DESIGN AND MODELING

A. Multilayer directional coupler

The multilayer directional couplers are fabricated on semi-insulating GaAs substrates at the University of Manchester. The semi-insulating GaAs substrate thickness is 500 μm with ε_r =12.9. A micrograph of a fabricated multilayer directional coupler is shown in Fig. 3. The length of the multilayer directional coupler was designed to be a quarter wavelength at a centre frequency of 24 GHz, giving 1.2 mm with an effective dielectric constant of 6.5. The widths of the conductors used are 26 μm and 14 μm, which are much wider than the conductors used in interdigitated couplers. Using ADS Momentum simulation, Table 1 shows the effects of varying the overlap at 14 GHz. By increasing the overlap area, the coupling factor is increased as a result of broadside coupling. Subsequently, this will also reduce the isolation; hence an overlap of 4 μm can be used as a tradeoff. Further increase in the isolation can be achieved by using a thicker polyimide, also shown in Table 1. From the simulation results it is clear that by increasing the polyimide thickness to around 2 μm, an isolation factor of 25 dB can be achieved. Further simulation results showed that increasing this by 3 μm the isolation could be improved to 30 dB.

B. Active couplers using pHEMTs

The coupler has been implemented on an MMIC using the Bookham Technology H40P GaAs process, with pHEMTs of 0.2 μm gate length and 60 μm gate width [1]. The active couplers are based on pHEMT distributed amplifiers without the 50 Ω gate and drain line terminations. To realize a 4-port coupler, removal of these terminations will allow the gate line to be used as a through path and the drain line as a coupled path. A series capacitor is connected to the gate line to set the coupling factor (Fig.2). The series capacitor acts as a potential divider and reduces the voltage across the gate terminal consequently reducing the gain. A 9.4dB reduction in gain is required to achieve a coupling factor of 5dB, requiring C1 = 0.1 pF at 10 GHz [1]. The inductors used were constructed from microstrip transmission lines with high characteristic impedance and short length. Fig. 4 shows a micrograph of the fabricated MMIC coupler. The use of a series capacitor, C1, with a low value of capacitance has two further advantages in this design. One attribute is that the cut-off frequency of the gate and drain artificial lines is increased and hence increasing the operational bandwidth. Furthermore, a small resultant gate capacitance leads to a small inductor being required to maintain 50 Ω characteristic impedance and hence short transmission lines between the active devices are required, reducing the overall size [4].

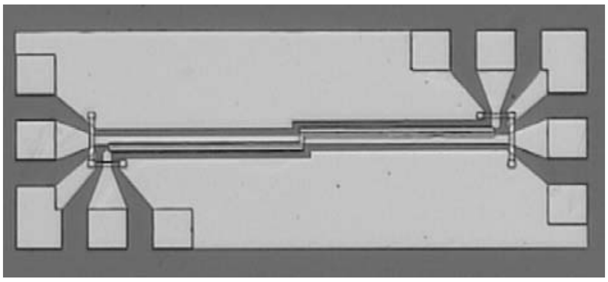

Fig. 3. Micrograph of a fabricated CPW multilayer directional coupler

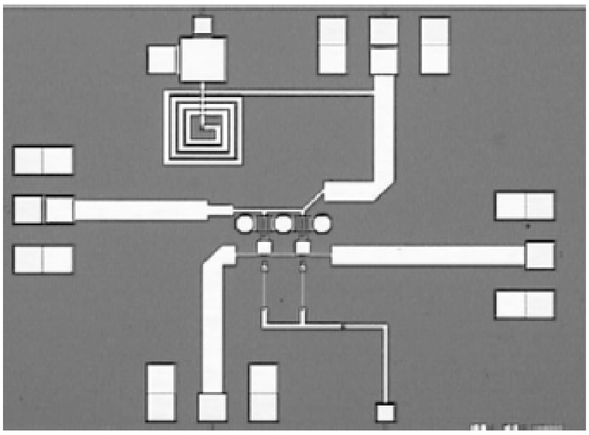

Fig. 4. Micrograph of fabricated planar active coupler based on pHEMTs

III. RESULTS AND DISCUSSION

A. Electrical Performance

The electrical performance of a coupler is determined by its coupling factor, isolation and directivity. Both the passive coupler and active coupler were designed for a coupling factor of 5 dB which has been achieved, as shown in Fig. 5 and Fig. 6. The active coupler achieves 5 dB coupling factor over more than three octaves. The passive coupler is also broadband, although its operating band has been designed for higher frequencies up to 40 GHz at the expense of lower frequency performance. A lower design centre frequency would be required to achieve lower frequency operation but this means longer coupled lines are required. On the other hand, there are no size implications in achieving low frequency performance with the active coupler.

	The effects of overlaps (μm)			Polyimide thickness (μm)	
Parameters	OL = 2	OL = 4	OL= 6	1.1	2
Isolation (dB)	27.91	22.99	20.13	14	25
Coupling (dB)	6.03	5.38	4.84	5.1	5.2
Directivity (dB)	21.89	17.61	15.29	11.1	17.2

TABLE I

MOMENTUM SIMULATION OF THE CPW MULTILAYER COUPLERS AT CENTRE FREQUENCY OF 14GHZ

It is necessary to maximise the coupler isolation. The multilayer passive coupler exhibits 10 dB isolation over the 10 - 40 GHz frequency band, shown in Fig. 7. It is clear from figure 5 and 7 that reasonable agreement between the measured and simulated results are obtained. The multilayer coupler is reciprocal, hence the transmission port and coupled port are isolated. In contrast, the active coupler is non-reciprocal and the isolation from the coupled port to the transmission port is greater than 26 dB, as shown in Fig. 8 but the isolation is poor (5 dB) from the transmission port to the coupled port. Therefore, the active coupler requires additional buffer circuitry on the transmission port to improve the isolation [4].

B. Active couplers using pHEMTs

An important factor in the MMIC implementation of couplers is the area of GaAs required to realise the design. The multilayer coupler requires a minimum area of 1.2 mm x 0.4 mm without meandering the transmission lines which could be employed to reduce the length. Implementation of this coupler also requires access to a MMIC process capable of multilayer topology. The active coupler has an intrinsic area of only 0.25 mm x 0.46 mm, although including bias elements means an area of 0.80 mm x 0.46 mm is required which would be regarded as satisfactorily small for most applications where high power and intermodulation is not an issue. Also, a standard MMIC technology process is sufficient to implement this circuit. Both couplers show some discrepancy between simulated and measured isolation values. The difference in the multilayer coupler is most likely due to thinning of the polyimide layers over the metal layers and this illustrates the need to control the dimensions of fine lines and gaps in this type of structure. The active coupler most likely suffers from coupling between the gate line and drain line which is not taken into account by the simulation model used; 2D or 3D modelling is required to solve this.

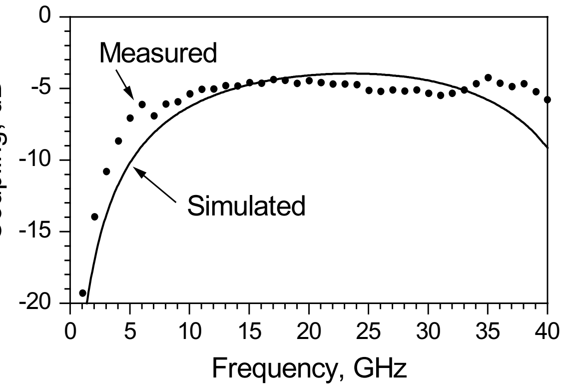

Fig. 5. Coupling factor of multilayer coupler, simulated results from ADS Momentum

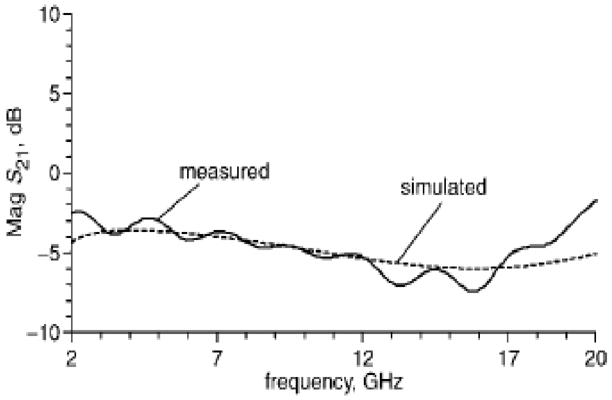

Fig. 6. Coupling factor of a distributed active coupler

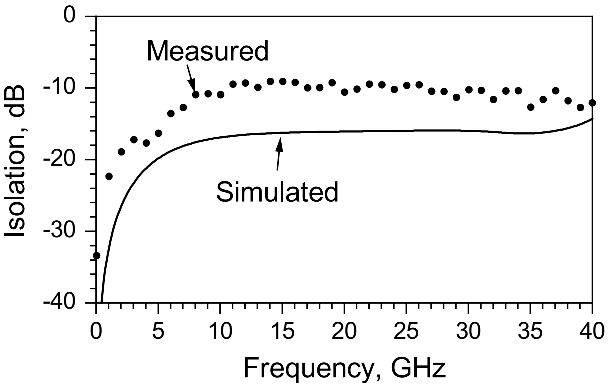

Fig. 7. Isolation of multilayer coupler , simulated results from ADS Momentum

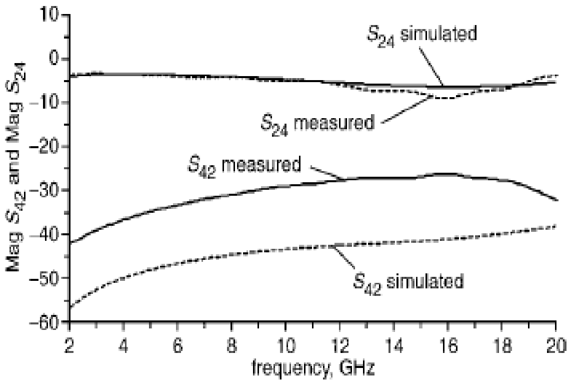

Fig. 8. Isolation between transmission port (port 4) and coupled port (port 2) for active coupler

IV. CONCLUSION

In this work two GaAs microwave couplers are designed, fabricated and tested. One is a passive coupler based on CPW multilayer circuits and the other is based on a MMIC pHEMT fabricated using a standard GaAs foundry process. In the design optimization of passive couplers it was shown that by varying the overlap area one could increase the coupling and by selecting the appropriate thickness of polyimide, the isolation can be significantly improved. This provides a flexible design for manufacturing inexpensive microwave couplers. A two-section distributed circuit has been fabricated using pHEMT devices and results show the feasibility of using distributed techniques to design MMIC couplers. In comparing the design and implementation of these two components, it was noted that both types of coupler have their relative merits and variations in implementation method. For the first time the comparison gives a useful guide to the most appropriate coupler for a given application.

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