An MMIC-Compatible Tightly Coupled Line Structure Using Embedded Microstrip

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***Abstract*—This paper presents a highly manufacturable coupled line structure for MMIC's which uses embedded microstrip to achieve tight coupling and employs the process steps necessary to make metal–insulator–metal (MIM) capacitors. Passive circuits demonstrated using this technique include a single-section 5–21 GHz broadband 3 dB coupler fabricated on both 75 and 125 μm thick GaAs substrates and a 6–15 GHz 90° Schiffman section fabricated on a 125 μm thick GaAs substrate. The coupler and the Schiffman section use tight (2 dB) to extremely tight (0.7 dB) coupling factors, respectively. Additionally, two single-section 2–7 GHz couplers are compared, one having a crossover and one without. This is the first time that a coupler has achieved such a wide bandwidth on thin GaAs substrates. Complete test data are presented, including the amplitude, isolation, and phase response of the couplers and the phase and amplitude response of the Schiffman sections.**

Introduction

QUADRATURE couplers are indispensible microwave components as they are used in phase shifters, balanced amplifiers, discriminators, mixers, baluns, and other microwave circuits. Many of these applications require broad-band 3 dB couplers which are traditionally realized using tightly coupled interdigitated multiconductor microstrip lines, such as the Lange coupler [1]–[3], and using the broadside-coupled structures [4]–[9]. Out of these couplers, only the Lange coupler configuration is compatible with monolithic microwave integrated circuit (MMIC) technology. In a Lange coupler, the conductor widths and the spacings between the coupler's conductors can be produced with standard thin-film manufacturing processes on thick low-dielectric constant substrates (thickness >250 μm, $\epsilon_r < 10$). However, on thin GaAs substrates used for MMIC's (thickness ~ 75–135 μm, $\epsilon_r = 12.9$), tightly coupled structures are difficult to realize because the conductor width and the spacing between the conductors become prohibitively small. For example, a process with a minimum line width of 8 μm and a minimum spacing of 8 μm cannot be used to fabricate a 3 dB Lange coupler on a 75 μm thick substrate because dimensions of approximately 4 μm are required. Other techniques, such as quasi-broadside coupled lines [10] and semireenterant sections [11], have been proposed as alternative techniques to achieve tight coupling with reasonable manufacturing tolerances. These coupled line structures require an extra dielectric layer, usually polyimide, whose thickness must be adjusted to control the coupling factor which does not allow other structures on the same substrate to use different coupling factors.

This paper presents a coupled line structure that uses embedded microstrip to achieve extremely tight couplings on thin substrates. Additionally, this structure allows each component on the same IC to use different coupling factors. Broad-band 3 dB quadrature couplers fabricated on 75 and 125 μm thick GaAs substrates and a Schiffman section fabricated on a 125 μm thick GaAs substrate demonstrate the capabilities of this structure. Because many circuits such as balanced amplifiers require the coupled and direct ports to be located on the same side of the coupler, a coupler with a crossover is fabricated and its performance is compared with a coupler without the crossover. The fabrication of these circuits does not require any extra processing steps for the typical MMIC process, as they are made with the same process steps as metal–insulator–metal (MIM) capacitors.

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Circuit Design

The coupling factor of multiconductor couplers can be increased by decreasing the spacing between the coupler's conductors. Typically, MMIC metallization processes use a plate-up technique that can achieve low loss and uniform spacings. The conductors, which are plated 4–5 μm thick, must have spacings between the conductors greater than 8 μm to achieve high yields. Unfortunately, dimensions of half this size are required for the realization of a 3 dB coupler on a 75 μm thick GaAs substrate.

The embedded microstrip coupled structure demonstrated in this paper mitigates the limitations of the photolithographic and plating processes. The embedded microstrip line coupler consists of two parallel strip conductors placed in close proximity, in which one strip is embedded in a dieletric. In this case, the parallel conductors can be placed very close or overlapped to each other. Fig. 1 shows a cross-sectional representation of an embedded microstrip coupled line structure that provides a coupling factor of 2 dB, and that can be used to make couplers having a bandwidth of several octaves. This structure consists of two 30 μm wide edge coupled conductors on the GaAs substrate. Fig. 2 contains a cross-

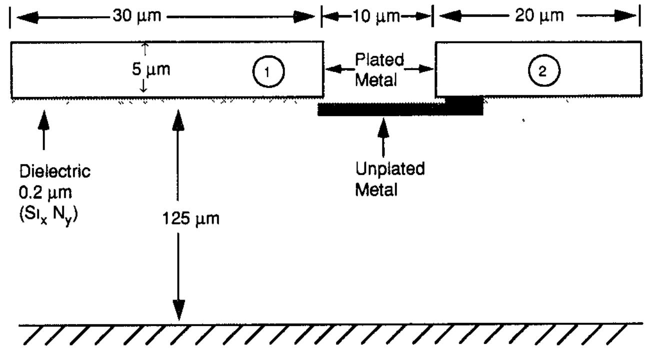


Fig. 1. Cross-sectional representation of the coupled line structure used to fabricate a 6–21 GHz coupler on a 125 μm GaAs substrate.

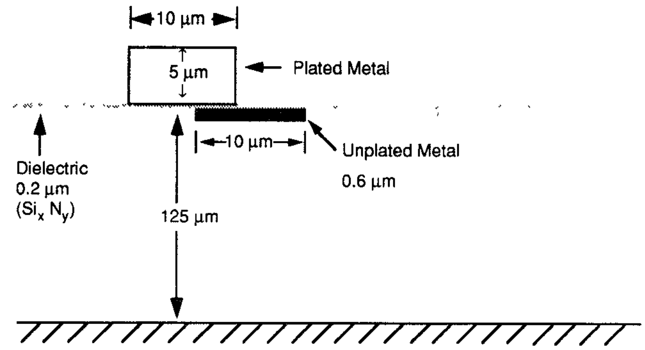


Fig. 2. Cross-sectional representation of the coupled line structure used to fabricate an octive bandwidth Schiffman section on a 125 μm GaAs substrate.

sectional representation of a very tightly coupled line structure used to realize a 90° Schiffman section. The Schiffman section employs a 90° coupled line shorted at one end, and is typically used in phase shifters. It provides 90° of insertion phase with respect to a 90° length of transmission line over a wide bandwidth. The bandwidth can be greater than an octave if an extremely tight coupling factor of approximately 0.7 dB is used. To achieve this extremely tight coupling factor, the conductors must be overlapped, forming an offset quasibroadside coupler. The conductors in this case overlap by 2 μm and are 10 μm wide. The conductor buried in the dielectric is too narrow to add any plating as the outside edge of this conductor is only 8 μm from the edge of the plate-up conductor.

The analysis of these coupled line geometries is difficult because the lines are asymmetrically edge coupled in the coupler's case, and offset asymmetrically broadside coupled to realize the Schiffman section. Approximate solutions of these structures can be obtained by using an electromagnetic simulator. In this case, "em"™ by Sonnet Software was used to analyze both structures. The design parameters for these two structures are summarized in Table I. CALMA plots of the 3 dB coupler and the 90° Schiffman section are shown in Fig. 3.

A 3 dB coupler was also designed with coupled and direct ports on the same side using a crossover, a configuration commonly used for the construction of balanced amplifier. The crossover, shown in Fig. 4 by a CALMA layout, uses an airbridge in addition to the process steps mentioned above. The crossover at the midpoint switches the embedded microstrip line to the plated microstrip line and vice versa. In the coupler, the length of the crossover is only 60 μm, and has a negligible effect on the coupler's performance.

Fabrication of Structures

The construction of these structures starts with the deposition of a thin (about 0.6 μm) strip of metal onto the GaAs, forming the lower portion of conductor 2 (Fig. 1). This process step forms the bottom plates of capacitors and the lower conductors in airbridge crossovers on MMIC's. Next, a dielectric, silicon nitride (Si_3N_4), is deposited covering the entire surface of the MMIC embedding the microstrip line. (This dielectric also serves as the insulator in the MIM capacitors.) Then, via holes are etched in the dielectric to connect the embedded conductors with metallization on the top side of the dielectric. The front side of the coupler is completed by adding the plated microstrip lines which are formed on the MMIC at the same time as the rest of the microstrip lines, inductors, and capacitor top plates. The plating for conductor 2 is a 20 μm wide line that connects to the embedded microstrip through the via. The separation of 10 μm (see Fig. 1) between the plated lines is dictated by the limits of the photolithographic process in order to achieve high yields using 4.5 μm thick plated conductors. The plated line connected to the embedded microstrip transmission line reduces the coupler's insertion loss. In manufacturing these structures, we used the stepper technique in which each die is patterned individually.

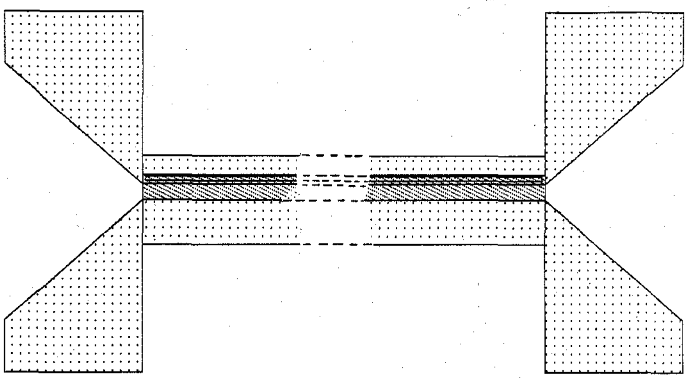
After completing the front side processing, the substrate was lapped to required thickness. The ITT standard MSAG process uses 125 μm GaAs substrate thickness for small-signal applications and 75 μm thick substrate for power applications in order to lower the device thermal resistance. Finally, the via holes through the substrate were etched and a thick gold layer was evaporated on the back side, followed by plating to form the ground plane. Fig. 5 shows a microphotograph of the 5–21 GHz coupler with the TRL test structures, and Fig. 6 shows a microphotograph of the crossover.

Test Results

The couplers were tested on-wafer using TRL deembedding techniques. Each of the couplers had one port terminated, by connecting a 50 Ω resistor to the ground through a via hole on the chip itself, forming a threeport test structure. Testing a threeport is much simpler than testing a four-port and, yet, the coupler can be completely characterized because it is a reciprocal device. Fig. 7 shows the measured performance (coupling and return loss at the three ports) of nine 6–21 GHz broad-band couplers tested in the 3 × 3 array on a 125 μm thick GaAs wafer. A maximum amplitude variation of ±1.5 dB was

TABLE I
THE PHYSICAL DIMENSIONS OF THE 3 dB COUPLER AND THE 90° SCHIFFMAN SECTION

Parameter	6–21 GHz 3 dB Coupler	2–7 GHz 3 dB Coupler	5–15 GHz 90° Schiffman Section	Unit
Conductor width	30	30	10	μm
Conductor length	1900	5700	5250	μm
Conductor overlap	0	0	2	μm
Plating thickness	4.5	4.5	4.5	μm
Dielectric layer's thickness	0.2	0.2	0.2	μm
Dielectric constant of dielectric layer	6.7	6.7	6.7	
Unplated metal thickness	0.6	0.6	0.6	μm
Substrate thickness	125	125	125	μm
Dielectric constant of substrate	12.9	12.9	12.9	



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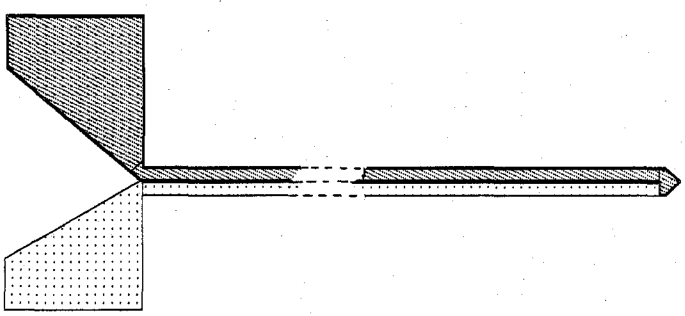


(b)

Fig. 3. CALMA layouts of two circuits using the embedded microstrip coupled line structures. (a) A multioctave bandwidth coupler using edge coupling. (b) A Schiffman section realized using an asymmetric broadsided coupled line structure.

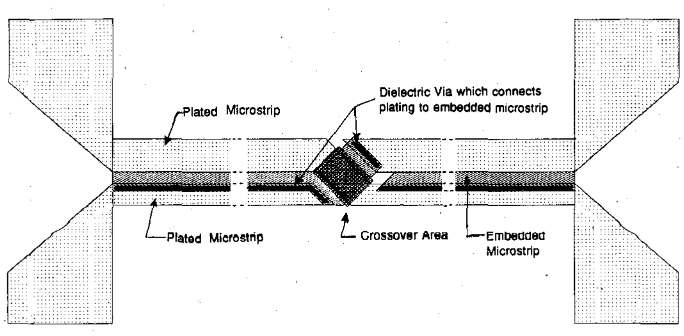


Fig. 4. Top view of a crossover for broad-band embedded microstrip coupler to bring the coupled and direct ports on the same side.

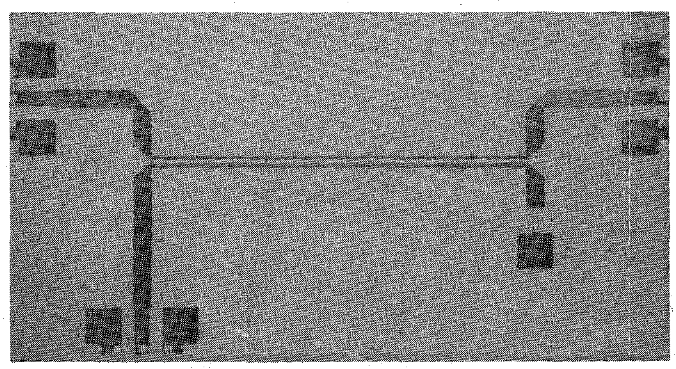


Fig. 5. A microphotograph of the 6–21 GHz 3 dB coupler in a TRL test structure.

achieved between the coupled and direct ports over a 16 GHz bandwidth. The measured return loss at all ports was greater than 13 dB from 0.5 to 24 GHz. The typical measured phase difference between the direct and coupled ports and the isolation between the input and isolated ports of this coupler as a function of frequency are plotted in Fig. 8. The phase difference is 93 $\pm$ 9°, and the isolation is better than 10 dB across the 0.5–20 GHz frequency range. Similar performance was measured on other wafers in different wafer lots.

The 5–21 GHz coupler was also fabricated and tested on a 75 μm thick GaAs substrate. Measured performance (coupling and return loss at three ports) of this coupler tested in the 3 $\times$ 3 array on a wafer is shown in Fig. 9. A maximum amplitude variation of $\pm$ 1.0 dB was achieved between the coupler and direct ports over 5 to 21 GHz frequency range (16 GHz bandwidth). The measured return loss at all ports was greater than 18 dB over the 0.5–21 GHz range and greater than 12 dB over the 0.5–26 GHz frequency range. A typical phase difference between the coupled and direct ports as a function of frequency is presented in Fig. 10, and is 92 $\pm$ 10° over the 0.5–17 GHz frequency range. The measured isolation for this coupler was greater than 10 dB over the 0.5–18 GHz frequency band.

A second set of couplers with and without a crossover having a length of 5700 μm to operate in the 2–7 GHz

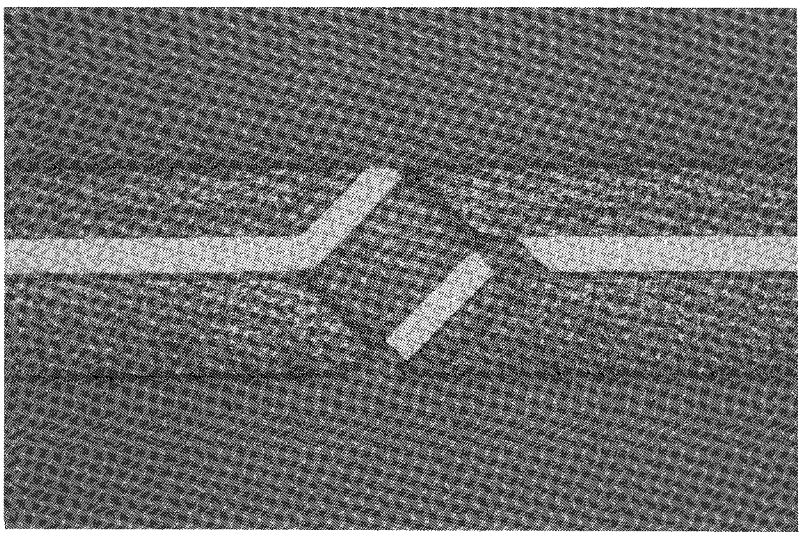
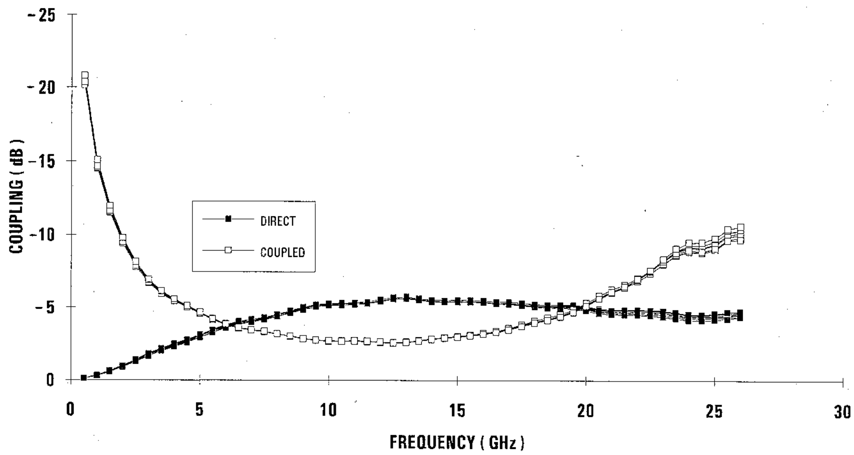
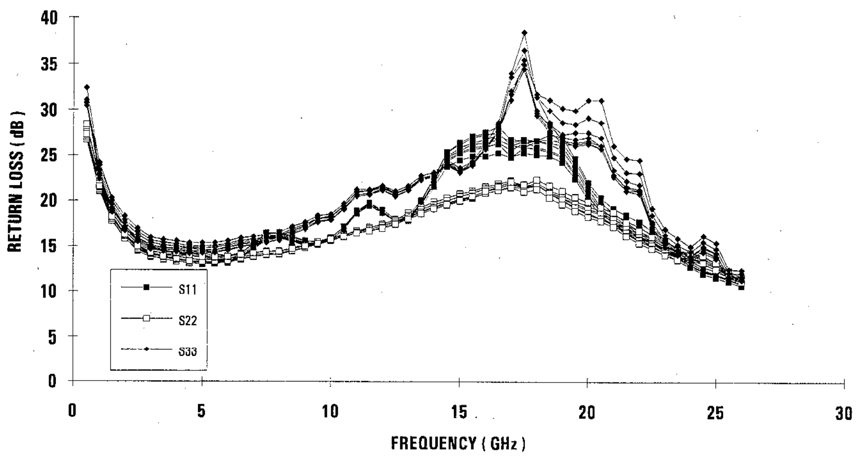


Fig. 6. A microphotograph of a crossover used to bring the coupled and direct ports on the same side.



(a)



(b)

Fig. 7. Measured performance of the 5–21 GHz coupler fabricated on a 125 μm thick GaAs substrate. (a) Coupling at coupled and direct ports. (b) Return loss at input, coupled, and direct ports.

band was constructed. The measured performance of several dozen of these couplers without crossover demonstrating the manufacturability of the tightly coupled structure has been reported earlier [12]. In this paper, we compare the performance of the 2–7 GHz coupler on a 125 μm thick GaAs substrate to determine if the crossover

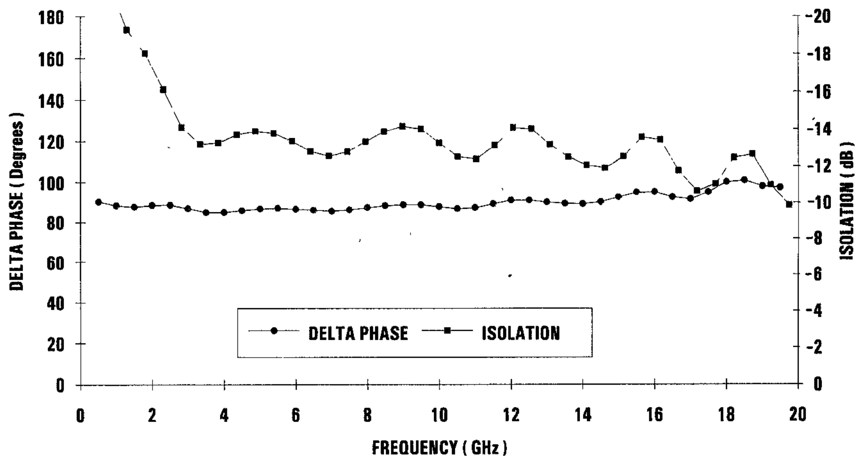
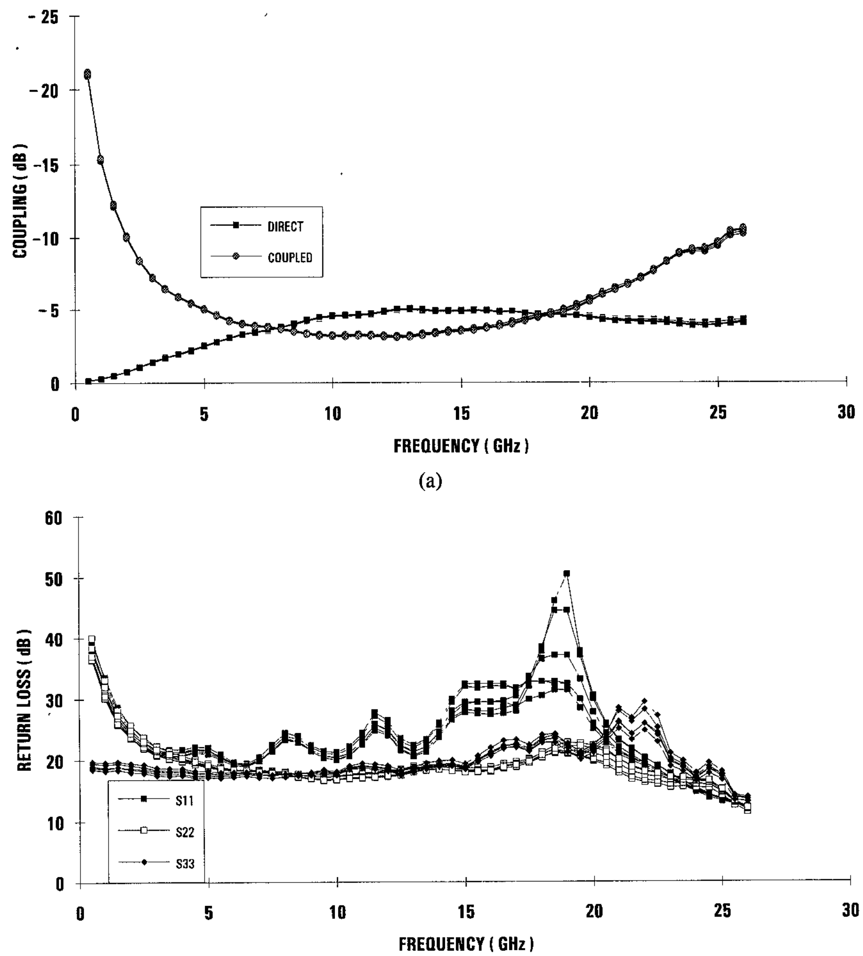


Fig. 8. Measured insertion phase difference between coupled and direct ports and isolation of the 5–21 GHz coupler fabricated on a 125 μm thick GaAs substrate.



(b)

Fig. 9. Measured performance of the 5–21 GHz coupler fabricated on a 75 μm thick GaAs substrate. (a) Coupling at coupled and direct ports. (b) Return loss at input, coupled, and direct ports.

would have any effect on electrical performance. Fig. 11 compares the typical measured performance of the two types of couplers. The differences between the two sets of performance are more attributable to manufacture variations than the crossover. Also, the insertion loss of each type of coupler is almost identical. Fig. 11 shows that the isolation of the coupler with a crossover is slightly degraded by approximately 1 dB.

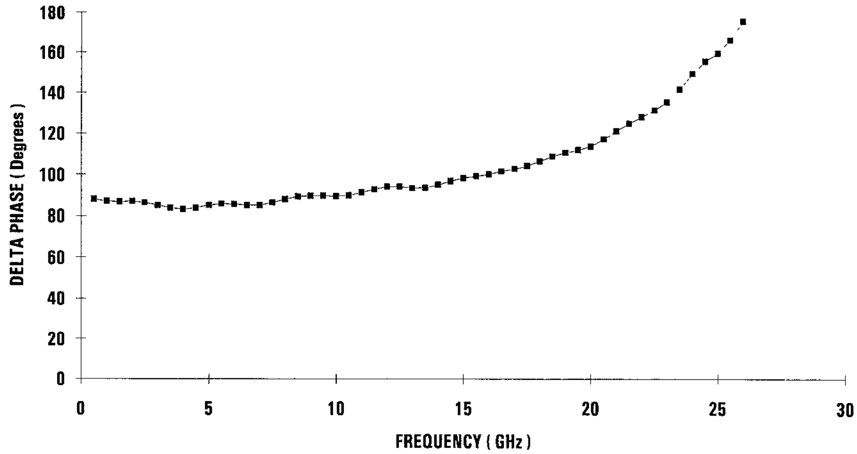
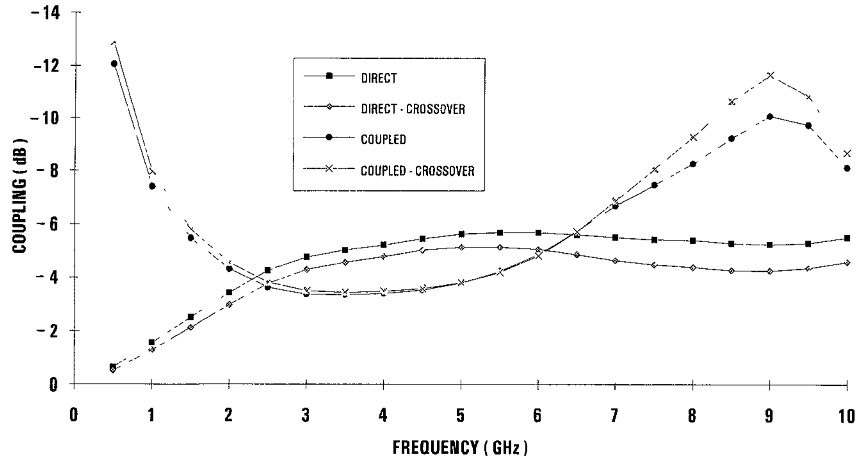
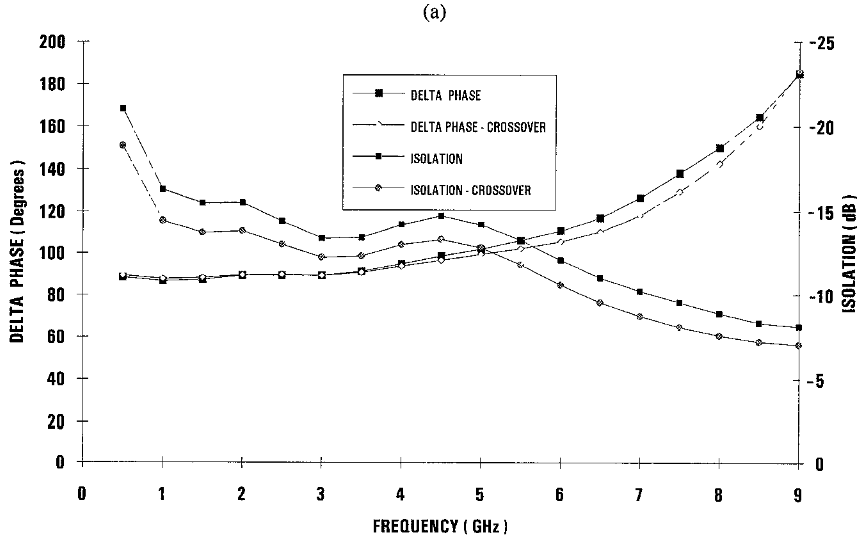


Fig. 10. Measured insertion phase difference between coupled and direct ports of the 5-21 GHz coupler fabricated on a 75 μm thick GaAs substrate.



(a)



(b)

Fig. 11. Comparison of measured performance of the 2-7 GHz coupler fabricated with and without crossover on a 125 μm GaAs substrate. (a) Coupling at coupled and direct ports. (b) Phase difference between the coupled and direct ports, and isolation.

The Schiffman section fabricated on a 125 μm thick GaAs substrate was also tested on-wafer using TRL deembedding techniques. Fig. 12 shows the phase response of this circuit compared to the phase response of a 90° length of 50 Ω microstrip line. The phase difference between these two responses is 90 ± 10° over the 6-15

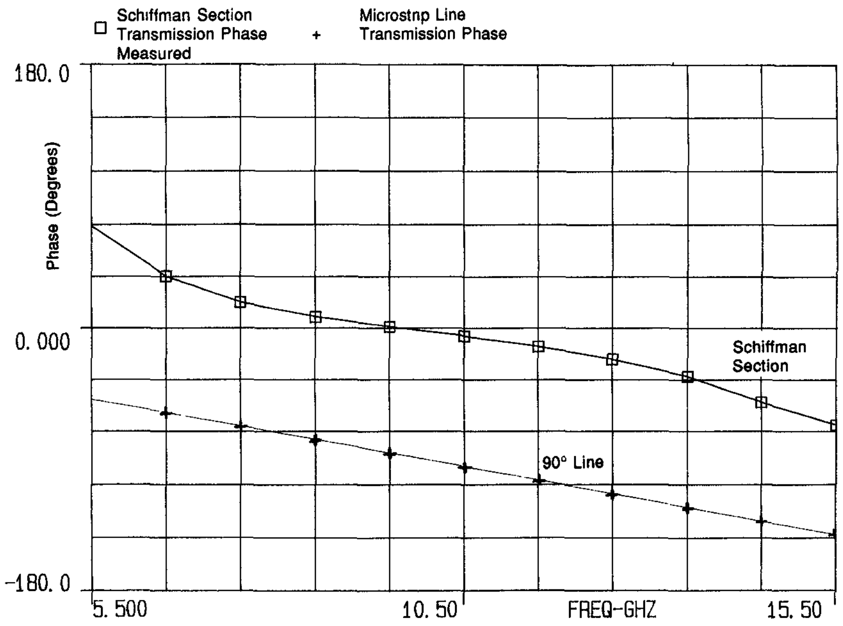


Fig. 12. The offset broadside coupled Schiffman section's phase response compared to the phase of a 90° transmission line.

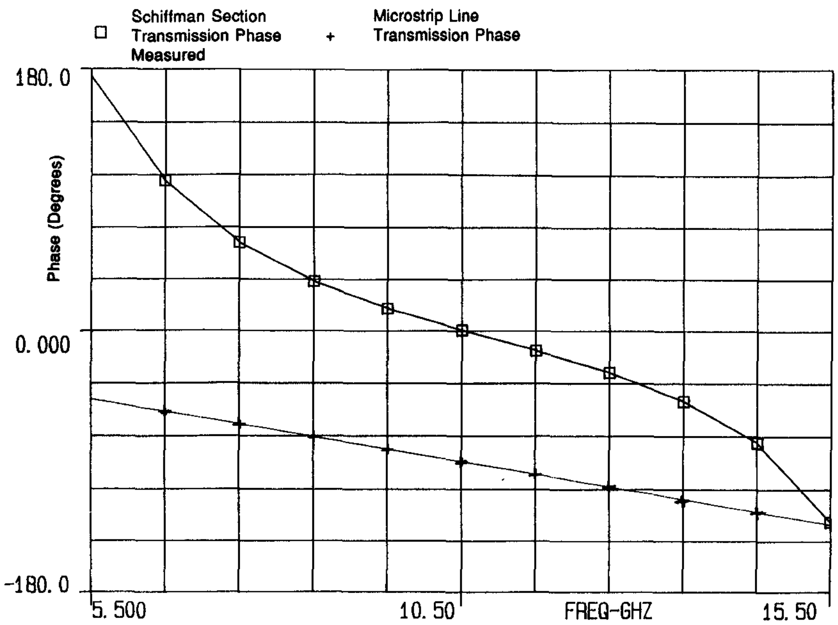


Fig. 13. The interdigital Schiffman section's phase response compared to the phase of a 90° transmission line.

GHz frequency range. The measured insertion loss of the Schiffman section was 2.5 dB at the midband. This loss is a little high due to the lack of plating on the embedded microstrip conductor. The insertion loss could be decreased by adding plating to the embedded microstrip. The measured return loss was better than 12 dB over the 6–15 GHz frequency range. As a comparison, the phase response of a Schiffman section constructed using a four-conductor interdigitated structure (similar to a Lange coupler) which used 8 μm wide lines and 8 μm spacings between the conductors on a 125 μm thick GaAs substrate is shown in Fig. 13. The bandwidth of this circuit is only 4 GHz compared to the 9 GHz achieved by using the tightly coupled structure.

Conclusion

We have demonstrated a coupled line structure that uses embedded microstrip to achieve extremely tight coupling factors. Other advantages of this structure are that its implementation is not limited by substrate thickness or dielectric constant, and that it uses the same process steps required to fabricate MIM capacitors on MMIC's. The test results for a 5–21 GHz single-section quadrature coupler on 75 and 125 μm thick substrates, a 2–7 GHz single-section quadrature coupler design with and without a crossover, and a 6–15 GHz Schiffman section have been presented in this paper. These results demonstrate the broadest bandwidths ever reported for these types of circuits on thin GaAs substrates, a tolerance to manufacturing variations, and a crossover design that does not degrade electrical performance. The dimensions of the coupler are easily realized and, therefore, they can be produced with excellent yield. This technique will allow a wider variety of broad-band circuits to be designed as MMIC's, e.g., mixers, phase shifters, balanced amplifiers, etc.

Acknowledgment

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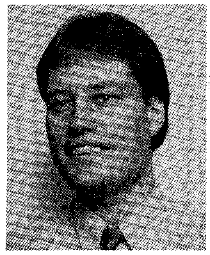

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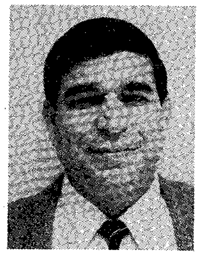

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