Multilayer MMIC Directional Couplers Using Thin Dielectric Layers

Seiichi Banba, *Member, IEEE,* and Hiroyo Ogawa, *Member, IEEE*

***Abstract*—Low-loss and small-sized MMIC directional couplers utilizing a multilayer structure composed of coupled thin-film transmission lines on a GaAs wafer surface are newly proposed. The fundamental characteristics of the couplers are discussed through calculations by numerical analysis, and the performance of the couplers and an application to reverse-phase hybrid ring are demonstrated. The results show that a 3 dB coupler can be designed within a 0.8 mm × 0.8 mm area for a center frequency of 20 GHz. Coupling losses of 3.7 dB ± 0.2 dB over a 4-GHz bandwidth and isolation of better than 26 dB in the frequency range of 0–30 GHz are achieved. The proposed coupler configurations can be applied to the high-density and multifunction integration of MMIC's.**

I. Introduction

DIRECTIONAL couplers are important elements as 90° power dividers and power combiners in microwave circuits such as balanced amplifiers, balanced mixers, and microwave signal processors. However, it is difficult to achieve tight coupling on microwave integrated circuits (MIC's). As an alternative, a branch-line hybrid constructed with four quarter-wavelength transmission lines can be employed as a 3-dB coupler. Nevertheless, its use in monolithic microwave integrated circuits (MMIC's) is limited due to its large size. To design multifunction, high-density, and cost-effective MMIC's, we must reduce the area of the hybrid.

Recently, a structure of thin-film transmission lines, which utilize narrow-width microstrip conductors on thin (several μm thick) dielectric materials fabricated over the ground metal on a GaAs wafer surface, was reported [1]–[7]. Thin-film transmission lines allow for high-density circuit integration because of reduced transmission line widths and their ready application to multilayer configurations. In addition, meander-like and crossover transmission line structures are easily fabricated in a small area. Therefore, a highly flexible circuit design can be achieved for a three-dimensional structure; this configuration is suitable for high-density integration of MMIC's. Thin-film transmission lines can also be integrated within uniplanar circuits, and are normally called multilayer MMIC's.

The initial applications of such a structure were small-sized hybrid rings such as branch-line and rat-race hybrids [2], [4], [5]. Quasi-lumped-element hybrid rings, which utilize combinations of short high-impedance transmission lines and shunt-lumped capacitors, have also been reported [8]. Although these hybrids have substantially reduced occupied areas, their excess coupling losses become large due to lossy transmission lines, and it is difficult to obtain balanced port characteristics and wide-band performance. Therefore, the performance of MMIC's using these hybrids is drastically deteriorated compared with those of conventional microwave circuits. It is necessary to achieve high-performance 90° hybrids without increasing the circuit area.

In this paper, the configurations of directional couplers utilizing thin dielectric layers fabricated on a GaAs wafer surface are proposed. The directional couplers are constructed with a multilayer structure consisting of coupled thin-film transmission lines with a tuning septum and floating conductor. The fundamental characteristics of the directional couplers are calculated by the quasi-static finite-element method (FEM) and full-wave FEM, and their suitability for use in microwave circuits is discussed. The transmission line loss dominated by conductor loss is also discussed to predict the frequency characteristics of the couplers. Some advantages of the proposed directional couplers are as follows: 1) excellent performance and design accuracy; 2) small size for use in MMIC's; 3) good compatibility with coplanar MMIC's; and 4) the possibility of loose coupling to tight coupling utilizing the same process. Finally, the design and performance of a 20-GHz tight coupler (such as −3 dB) and a medium coupler (such as −6 dB) are presented, and an application to a reverse-phase hybrid ring employed as a 180° hybrid is demonstrated.

II. Directional Coupler Design

The major problem in the directional couplers based on parallel-coupled transmission lines is realization of tight coupling. This problem can be solved by fabricating a floating potential conductor over a dielectric overlay to reduce the odd-mode impedance [9], or by using a ground conductor with a tuning septum to increase the transmission line impedance [10]. In order to achieve a tight coupler that can maintain a high performance and reduce its occupied area, we combine these methods and fabricate the structure on a GaAs wafer surface utilizing a multilayer MMIC process.

The multilayer structure consists of polyimide films for the thin dielectric layers and 1-μm-thick gold films for the conductor metals. The process for polyimide film preparation and subsequent chemical etching was described in [11]. This process can generate cone-shaped via holes which connect the

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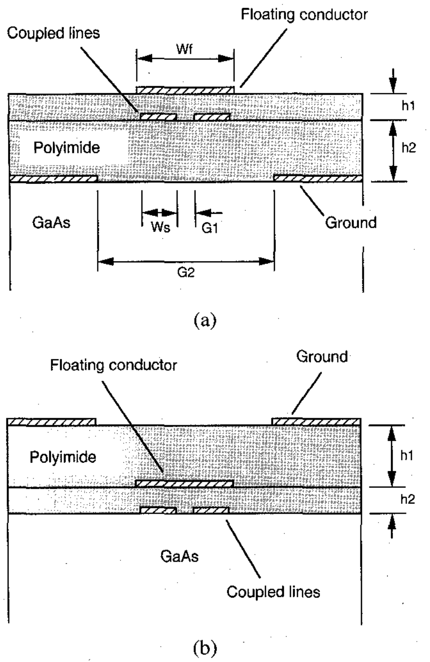


Fig. 1. Cross-sectional views of multilayer MMIC directional couplers. (a) Normal type and (b) inverted type.

microstrip conductors on the upper dielectric layers with the input/output ports and ground plane on the GaAs substrate. The relative dielectric constant and loss tangent of the polyimide film are 3.7 and 0.01 (10 MHz), respectively. A uniformity in the thickness of better than 1% is obtained up to 10 μm. The measured stress of the polyimide film is a constant value of -2.4×10^8 dyn/cm^2, and is one-tenth that of Si_3N_4 and SiO_2 films. Furthermore, the surface of the films, which are formed by spin coating, is flat due to its high viscosity. These properties show that polyimide film is a suitable dielectric material for multilayer MMIC fabrication. In our fabrication, the multilayer structure consists of four 2.5-μm-thick polyimide films; therefore, conductors can be formed up to five layers.

Cross-sectional views of multilayer MMIC directional couplers are shown in Fig. 1(a) (normal type) and Fig. 1(b) (inverted type). The directional couplers are constructed with coupled microstrip lines, a ground conductor with a tuning septum, and a floating conductor located over the microstrip lines. Each conductor is formed on a different dielectric layer. Since the floating conductor is located symmetrically over the microstrip lines, it works as a cold-wall (ground plane) in the odd mode.

In the even mode, the potential of the floating conductor becomes close to that of the coupled microstrip lines because the even-mode characteristics should not be changed substantially by the presence of the floating conductor. In the design, the even- and odd-mode characteristics in the coupled section must be evaluated. The characteristic impedance and guided wavelength of each mode are calculated by quasi-static FEM. Because these structures are small in comparison to the guided wavelength, quasi-TEM wave approximation can be used for numerical analysis. The desired coupling C and transmission line impedance Z_0 are written by the following equations:

$$C = 20 \log \left(\frac{Z_{\text{even}} - Z_{\text{odd}}}{Z_{\text{even}} + Z_{\text{odd}}} \right) \tag{1}$$

$$Z_0 = \sqrt{Z_{\text{even}} Z_{\text{odd}}} \tag{2}$$

where Z_{even} and Z_{odd} are the even-mode impedance and odd-mode impedance, respectively. In an inhomogeneous medium, the coupling length L_c is determined by the mean of the even-mode and odd-mode quarter wavelengths

$$L_c = \frac{1}{4} \cdot \frac{\lambda_{\text{even}} + \lambda_{\text{odd}}}{2}. \tag{3}$$

To calculate the circuit performance, we simulate the frequency characteristics of the transmission line attenuation with a commercially available CAD software package that includes user defined function routine (Touchstone). The frequency characteristic of the total attenuation per unit length $\alpha(f)$ is given by the following equation:

$$\alpha(f) = \alpha_c(F) \cdot \sqrt{\frac{f}{F}} \cdot \frac{1 - e^{-tK\sqrt{F}}}{1 - e^{-tK\sqrt{f}}} + \alpha_d(F) \cdot \frac{f^2}{F^2} \text{ [dB/mm]} \tag{4}$$

where F (in our case: $F = 20$ GHz) is the design frequency, and $\alpha_c(F)$ and $\alpha_d(F)$ are the conductor loss and dielectric loss at the design frequency, respectively. The t and K are conductor thickness and material constant $(= \sqrt{\pi\sigma\mu})$, respectively. The conductor losses of the directional coupler, which dominate in the odd mode, are calculated by the full-wave FEM [12] at the design frequency of 20 GHz. In our calculation, the skin effect is considered because the conductor thickness is approximately two times greater than the skin depth of the conductor at 20 GHz. The surface resistivity of the conductors and loss tangent of the polyimide films at 20 GHz are assumed to be 4.6×10^{-6} $\Omega \cdot$ m and 0.02, respectively. We also assume the surface roughness of the conductors to be zero from observations by scanning electron microscopy (SEM).

III. Coupled Section

Fig. 2 shows the calculated characteristic impedance and normalized guided wavelength of normal-type couplers in the even and odd modes as a function of tuning septum width, when the polyimide film thicknesses are $h1 = 2.5$ μm and $h2 = 7.5$ μm, respectively. To simplify the design and pattern layout, the distance between microstrip lines and width of the floating conductor are kept as $G1 = 10$ μm and $Wf = G1 + 2Ws + 4$ μm, respectively. The even-mode characteristics are strongly dependent on the tuning septum. For example, the even-mode impedance of these coupled transmission lines, whose tuning septum widths range from 40–200 μm, are between 70 and 150 Ω when the microstrip conductor width is 15 μm. On the other hand, the odd-mode characteristics have little effect on the tuning septum. To achieve a 3 dB coupler with 50 Ω impedance, the widths of the microstrip line and tuning septum are $Ws = 15$ μm and $G2 = 110$ μm, respectively. The polyimide film thickness dependence is shown in Fig. 3. The ratio of even- to odd-mode

TABLE I
STRUCTURAL PARAMETERS AND CALCULATED EVEN- AND ODD-MODE CHARACTERISTICS OF SEVERAL COUPLED SECTIONS (*: INVERTED TYPE STRUCTURE). THE CONDUCTOR LOSSES ARE CALCULATED AT 20 GHz

	Structural parameters [μm]				Calculated characteristics						
					Coupling [dB]	Characteristic impedance [Ω]		Effective dielectric constant		Conductor loss [dB/mm]	
	h1	h2	Ws	G2		Even	Odd	Even	Odd	Even	Odd
(1)	2 5	7.5	15	110	-2.99	122.6	20.9	4 657	3.876	0.251	0.808
(2)	5 0	5 0	27	220	-3.01	120.6	20.7	5.962	4.302	0 241	0 464
(3)*	7.5	2.5	10	120	-3.05	120.9	21 0	6.450	6 013	0.421	1 105
(4)	2.5	7.5	10	40	-5.70	87.4	27.7	3 711	3 806	0.324	0.788
(5)	5.0	5.0	16	70	-6.18	86.3	29.5	4 723	4.230	0.262	0.462

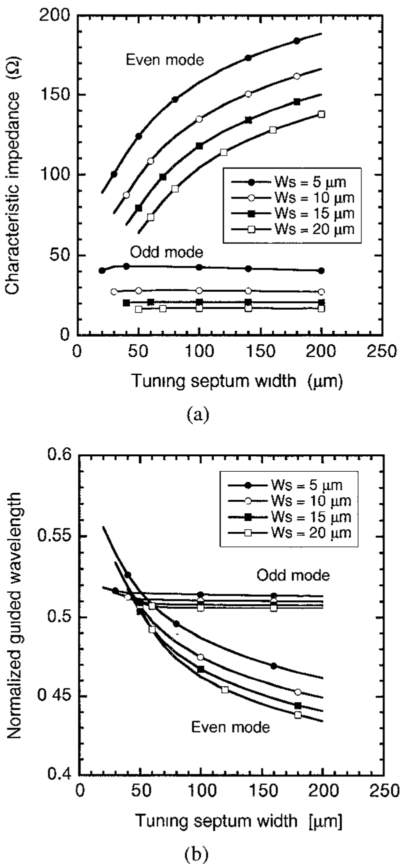


Fig. 2. (a) Calculated characteristic impedance and (b) normalized guided wavelength of normal-type structures as a function of tuning septum width ($h1 = 2.5$ μm, $h2 = 7.5$ μm).

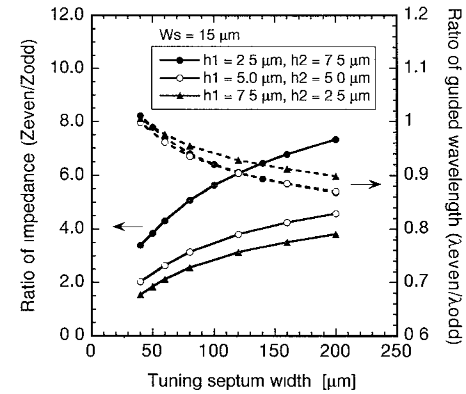


Fig. 3. Polyimide film thickness dependence of the ratio of even- and odd-mode impedance and guided wavelength.

TABLE II
STRUCTURAL PARAMETERS AND CALCULATED CHARACTERISTICS OF THIN-FILM TRANSMISSION LINES FOR USE IN A MULTILAYER BRANCH-LINE HYBRID. THE CONDUCTOR LOSSES ARE CALCULATED AT 20 GHz

Transmission line structure	Structural parameters [μm]		Calculated characteristics		
	Polyimide thickness	Line width	Characteristic impedance [Ω]	Effective dielectric constant	Conductor loss [dB/mm]
Microstrip line	5.0	10	50.1	2 870	0 398
Inverted microstrip line	5.0	10	35.0	5.962	0.590

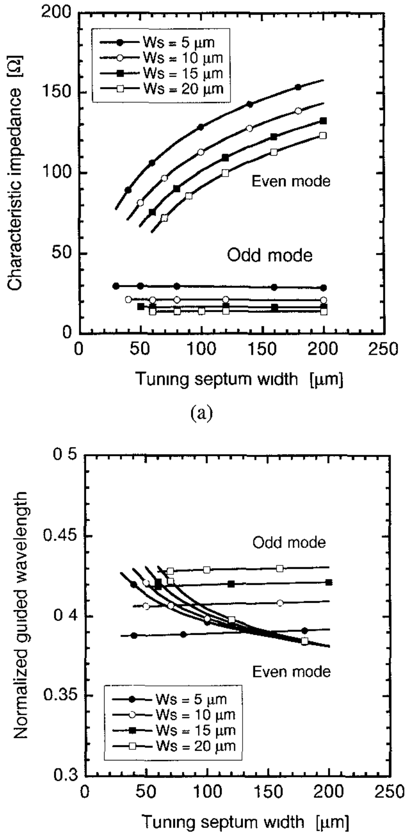
impedance becomes small with increasing distance between floating conductor and microstrip lines; it becomes large with increasing microstrip width.

Directional couplers based on parallel-coupled transmission lines using an inhomogeneous medium have different guided wavelengths in each mode. In general, the effective dielectric constant in the even mode becomes larger than that in the odd mode, and this phenomenon is emphasized for tight couplings. The difference in guided wavelengths degrades the coupler performance. The inverted-type coupler has a different arrangement of conductors as shown in Fig. 1(b). The coupled microstrip lines are formed on the GaAs wafer surface, and the ground plane is formed over the dielectric layers. In this structure, the effective dielectric constant in the odd mode can be increased because the electric field concentrates near the GaAs substrate. In addition, the effective dielectric constant in the even mode is not substantially increased. Therefore, the inverted-type coupler can achieve tight coupling while maintaining the even- and odd-mode velocity matching. The calculated characteristic impedance and normalized guided wavelength of inverted-type couplers are shown in Fig. 4. The inverted-type couplers show relatively small even- and odd-mode impedances; however, the difference in guided wavelengths in each mode becomes small compared with that of the normal-type couplers. For example, the ratio of guided wavelength ($= \lambda_{\text{even}}/\lambda_{\text{odd}}$) becomes 0.966 in an inverted 3-dB coupler, while the ratio becomes 0.912 for the normal type (see Table I).

Table I summarizes the structural parameters and calculated characteristics of several coupled sections. The widths of the microstrip lines and tuning septum become large in the design

TABLE III
CALCULATED PERFORMANCE OF 3-dB COUPLERS AND A MULTILAYER BRANCH-LINE HYBRID

Structure	Calculated results [dB]		
	Coupling losses	Return loss	Isolation
3 dB-coupler (1)	3.75 ± 0.05	> 26	> 26
3 dB-coupler (2)	3.6 ± 0 1	> 23	> 22
3 dB-coupler (3)	3.95 ± 0.05	> 29	> 29
Multilayer branch-line	5 4 ± 0.2	> 17	> 15



(b)

Fig. 4. (a) Calculated characteristic impedance and (b) normalized guided wavelength of inverted-type structure as a function of tuning septum width ($h1$=7.5 μm, $h2$= 2.5 μm).

of 3-dB couplers with increasing $h1$, and the even- and odd-mode velocity ratios are not well matched. This results in a degradation of the wide-band performance; however, the conductor losses in the odd mode become smaller than that of others. Therefore, the structures are suitable for medium and tight couplers with low loss. To compare the performance, we simulate the characteristics of the proposed coupler and the multilayer branch-line hybrid reported in [4], using values from Tables I and II. The calculated coupling losses, return loss, and isolation of the circuits are summarized in Table III. Although both circuits employ thin-film transmission line structures, the coupling losses of the proposed coupler are approximately 1.8 dB smaller than those of the hybrid ring at a center frequency of 20 GHz. This is caused by the usage of four quarter-wavelength transmission lines in the hybrid ring. By reducing the total transmission line length, we an obtain excellent performance within a small area.

On the basis of the calculations, it is easy to determine the widths of the coupled microstrip lines and location of the floating conductor corresponding to the odd-mode characteristics, and the tuning septum in the ground conductor corresponding to the even-mode characteristics. In addition, the proposed configurations have excellent design flexibility since various structures can be fabricated utilizing a multilayer MMIC process. For example, a loose coupling of less than -30 dB can be obtained by removing the floating conductor and tuning septum, and by using a structure of coupled triplate lines.

IV. PERFORMANCE

A 3-dB coupler [type (1) in Table I] is designed for a center frequency of 20 GHz and fabricated on a GaAs wafer surface. A microphotograph of the fabricated coupler is shown in Fig. 5. The chip size is very small, e.g., 1.1 mm × 1.1 mm including CPW input/output ports for measurements. The coupling length of the structure is 1820 μm, and the coupled section has a meander-like configuration to reduce the circuit area. Each microstrip conductor is connected to the CPW input/output ports on the GaAs wafer surface through via holes (15 μm × 15 μm). The couplers are tested using on-wafer probes and an HP8510B network analyzer. Termination probes, whose return losses are better than 20 dB up to 40 GHz, are also used. Frequency characteristics of the coupler are shown in Fig. 6(a) and (b). The calculated values are also plotted in the figures, including discontinuities in the transition regions between the coupled sections and input/output ports. The coupler shows coupling losses of within 3.7 dB ± 0.2 dB, and the phase difference between coupling port and through port is 91° ± 1° in the frequency range of 18–22 GHz. Furthermore, isolation is better than 26 dB and return losses are better than 22 dB in the frequency range of 0–30 GHz. Excellent performance is obtained, while the chip size is slightly larger than those of previous reports [4], [8]. Similarly, an inverted 3-dB coupler [type (3) in Table I] is also fabricated, and show coupling losses of 4.0 dB ±0.1 dB in the frequency range of 18–22 GHz. The directional coupler can be applied to balanced amplifiers and image-rejection mixers with no degradation in circuit performance and increase in circuit area. A 6-dB coupler is fabricated and measured. Coupling loss of 6.8 dB ± 0.2 dB, return losses of better than 22 dB, and isolation of better than 25 dB are obtained in the frequency range of 18–22 GHz.

In general, a rat-race hybrid, which is constructed with one 3/4-wavelength and three 1/4-wavelength transmission lines, is employed as a 180° coupler in microwave circuits. However,. such a hybrid using thin-film transmission lines shows unbalanced port characteristics and a relatively large insertion loss

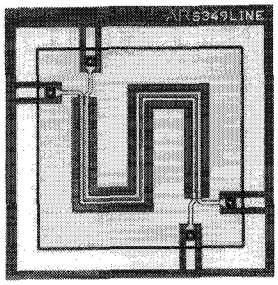


Fig. 5. Microphotograph of a fabricated 3-dB coupler.

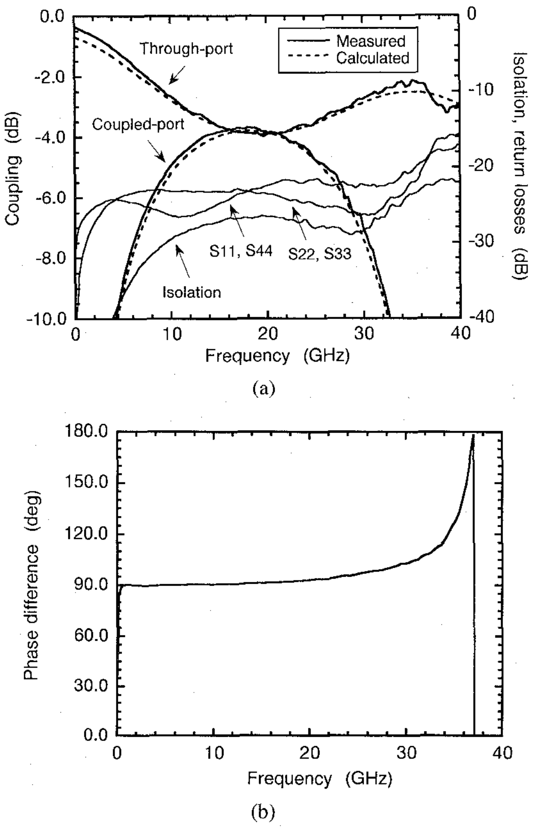


Fig. 6. Measured characteristics of a fabricated 3-dB coupler. (a) Coupling losses, return losses, and isolation. (b) Phase difference.

because of the 3/4-wavelength line whose loss is three times that of the others. To solve these problems and to demonstrate the ability of multilayer MMIC structures, we design a reverse-phase hybrid ring [14] replacing the 3/4-wavelength line of the rat-race hybrid with a 1/4-wavelength coupled section. The circuit diagram and measured characteristics are shown in Figs. 7 and 8, respectively. The intrinsic chip area is 2.3 mm $\times$ 0.5 mm. The hybrid ring consists of one coupled section ($Z_{\text{even}} = 159\ \Omega$, $Z_{\text{odd}} = 27\ \Omega$) and three 70 Ω transmission lines. All microstrip conductors are formed on the same dielectric layer to avoid junction discontinuities. The hybrid ring shows measured coupling losses of within 5.3 dB $\pm$ 0.5 dB. Return losses and isolation are better than 17 and 20 dB, respectively, in the frequency range of 18–22 GHz. Good performance is obtained using the proposed coupler configurations. Phase conditions in the out-of-phase and in-phase operations are 170° $\pm$ 5° and 5° $\pm$ 2°, respectively.

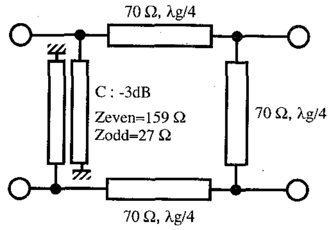


Fig. 7. Circuit diagram of a reverse-phase hybrid ring.

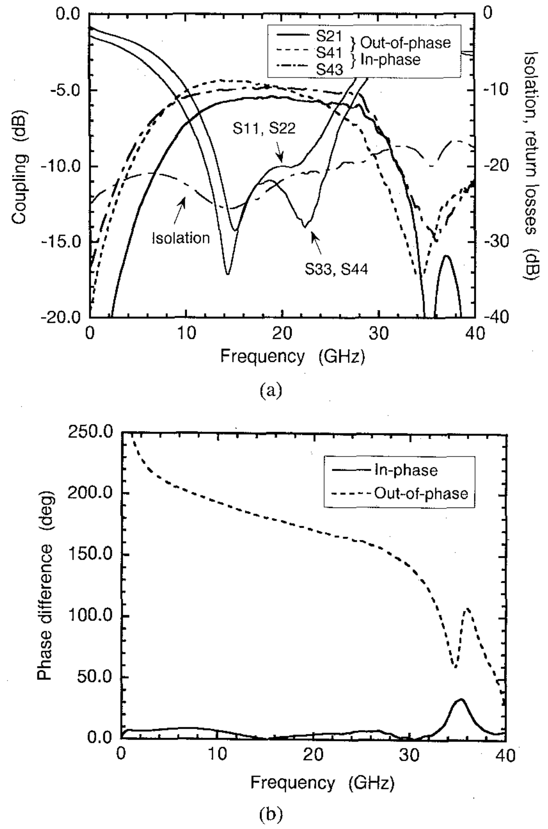


Fig. 8. Measured characteristics of a fabricated reverse-phase hybrid ring. (a) Coupling losses, return losses, and isolation. (b) Phase differences.

The differences from ideal performance are caused by parasitic inductors between the coupled section and short end.

V. Conclusion

Small-sized multilayer MMIC directional couplers using coupled thin-film transmission line structures composed of thin dielectric layers on a GaAs wafer surface have been proposed, and their performance and application have been demonstrated. 20-GHz band couplers have been designed within small areas, less than 1.0 mm^2, while excellent performance has been maintained. The proposed coupler configurations can be applied to the high-density and multifunction integration of MMIC modules such as balanced circuits and RF signal processing circuits.

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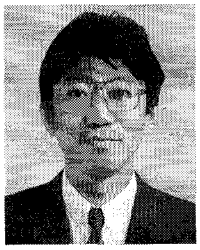

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