Uniplanar MMIC Hybrids—A Proposed New MMIC Structure

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***Abstract*—A new "uniplanar" circuit configuration[1] for monolithic microwave integrated circuits (MMIC's) has been proposed. It uses a combination of coplanar waveguides and slotlines on one side of the substrate. The key components for the uniplanar structure are air bridges, which provide T junctions and transitions from coplanar waveguides to slotlines or vice versa. Novel hybrid circuits such as a magic T and a branch-line coupler have been fabricated and tested at *K*-band, and good performance has been achieved. This new circuit configuration is promising for applications in other microwave circuits.**

I. Introduction

THE DEVELOPMENT of high-performance and low-cost microwave circuit equipment has been required for new radio communication systems. Microwave integrated circuits (MIC's) have been successfully used in developing the 26-GHz band transmitter/receiver [1]. MIC technology can offer great improvements in radio equipment size and cost. In addition, monolithic MIC's (MMIC's) are expected to reduce the size and cost of microwave circuits even more [2]. In the majority of MMIC's developed so far, microstrip lines have been used as the main transmission line, because characteristics of microstrip lines are well known and because a number of discontinuity problems are analyzed. However, coplanar waveguides or slotlines fabricated on one side of the substrate have not generally been used for MMIC's [3].

In this paper, new "uniplanar" circuit configurations for MMIC's are proposed. They employ a combination of coplanar waveguides and slotlines and use only one side of the substrate. The uniplanar MMIC has the same functions as the double-sided MIC [4]–[7]. The double-sided MIC uses a combination of microstrip lines and slotlines on both sides of the substrate. Its circuit configuration was successfully used in the development of the balanced modulator [4], the balanced up-converter [5], the magic T [6], and power dividers [7]. However, the double-sided circuit configuration is not suitable for MMIC's because it uses the back side of the substrate. Features of the uniplanar MMIC are summarized below.

1) The fundamental components are coplanar waveguides, slotlines, and air bridges.

2) The air-bridge circuit which connects coplanar waveguides with slotlines does not deteriorate the circuit performance at *Ka*-band.

3) No via holes are needed to connect active devices with the ground conductor.

4) The simple balance/unbalance transition circuit [8], [9] can be obtained by a combination of the unbalanced line (coplanar waveguide) and the balanced line (slotline).

5) The circuit fabrication process is the same as that of conventional MMIC's.

II. Uniplanar MMIC

On uniplanar MMIC's, coplanar waveguides and slotlines are fabricated on one side of the substrate. The propagating mode on the coplanar waveguide is the quasi-TEM mode [10] and that on the slotline is the TE mode [11]. An advantage of this difference and of the precise MMIC air-bridge technique is that a number of T junctions and transition circuit can be produced [12]. The other advantage of these transmission lines is the ease of grounding FET devices. This is because the transmission lines have the earth conductor on the same side of the substrate. This makes it possible to make MMIC's without via hole processes.

A. Uniplanar MMIC T Junction

The basic components for the uniplanar MMIC are illustrated in Figs. 1 and 2. Fig. 1 shows T junctions and their equivalent circuits, and Table I summarizes the relation between the input phase and the output phase of each T junction. The uniplanar MMIC can have both parallel and series T junctions using only one side of the substrate. This is a great advantage in developing hybrid circuits and balanced circuits.

When the input transmission line is the coplanar waveguide (Fig. 1(a)–(c)), the T junctions behave as an in-phase divider. The arrows show the schematic expression of the electric field in the slotline. Fig. 1(a) shows the configuration of the coplanar waveguide parallel T junction. Two air bridges are used to connect the outer conductor of the coplanar waveguide. Air-bridge reactance can be made negligibly small by miniaturizing the junction and line width. Fig. 1(b) and (c) shows the T-junction configurations from the coplanar waveguide to the slotlines and the coupled slotlines, respectively. The even mode of the coupled slotline is excited in phase by the coplanar waveguide.

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[1] Since the circuit utilizes only one substrate surface, it will be called a uniplanar cirucit.

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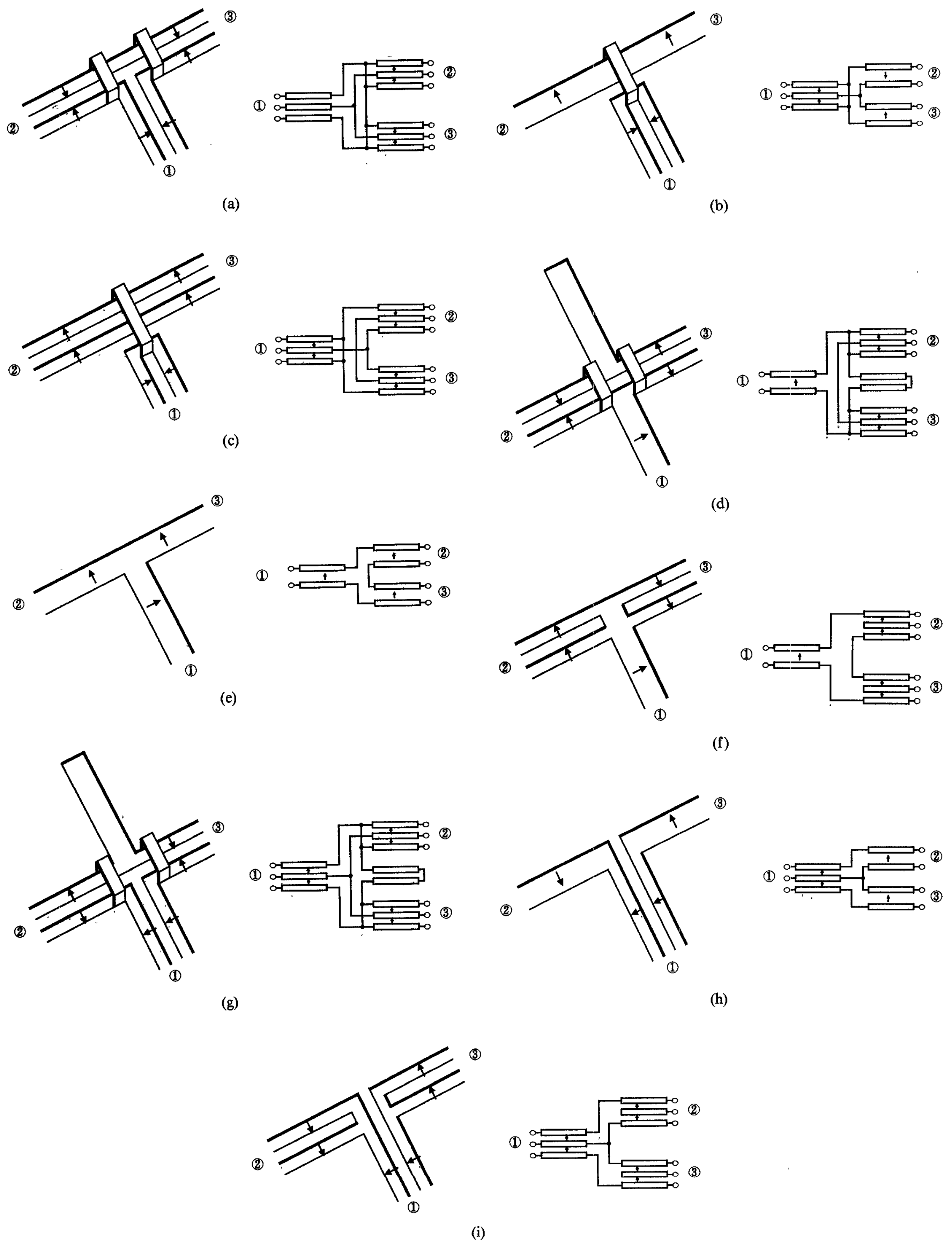


Fig. 1. Uniplanar MMIC junctions and their equivalent circuits. (a) Coplanar waveguide T junction. (b) Coplanar waveguide/slotline junction. (c) Coplanar waveguide/coupled slotline junction. (d) Slotline/coplanar waveguide junction. (e) Slotline T junction. (f) Slotline/coupled slotline junction. (g) Coupled slotline/coplanar waveguide junction. (h) Coupled slotline/slotline junction. (i) Coupled slotline T junction.

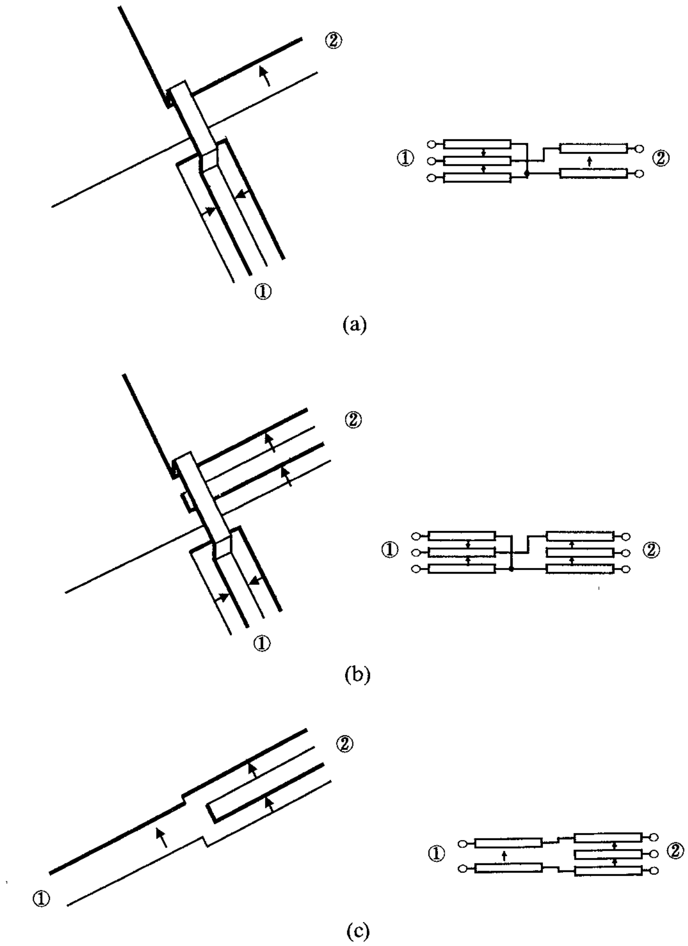


Fig. 2. Uniplanar MMIC transition circuits and their equivalent circuits. (a) Coplanar waveguide/slotline transition. (b) Coplanar waveguide/coupled slotline transition. (c) Slotline/coupled slotline transition.

When the input transmission line is the slotline (Fig. 1(d)–(f)), the T junctions behave as an out-of-phase divider. Fig. 1(d) and (f) shows the T-junction configurations from the slotline to the coplanar waveguide and the coupled slotlines, respectively. A short-circuited quarter-wavelength slotline between the air bridges is necessary for electrical separation of two output coplanar waveguides or two output coupled slotlines. The conventional slotline T junction shown in Fig. 1(e) also plays an important role in MMIC's. The other T junctions whose input transmission lines are coupled slotlines are shown in Fig. 1(g)–(i). These T junctions behave as out-of-phase dividers.

B. Uniplanar MMIC Transition Circuit

The other basic components for the uniplanar MMIC are the transition circuits from the coplanar waveguide to the slotline or vice versa. Fig. 2 shows the circuit configurations and their equivalent circuits. Table II summarizes the input and output transmission lines of the transition circuits. The coplanar waveguide/slotline and the coplanar waveguide/coupled slotline transition circuits are shown in Fig. 2(a) and (b). These circuits need the open circuit for matching. Fig. 2(c) shows the slotline/coupled slotline transition. No air bridges are needed to connect the slotline with the coupled slotline.

TABLE I
UNIPLANAR MMIC T JUNCTION

input transmission line \ output transmission line	coplanar waveguide	slotline	coupled slotline (even mode)
coplanar waveguide	parallel (a)	parallel (b)	parallel (c)
slotline	series (d)	series (e)	series (f)
coupled slotline (even mode)	series (g)	series (h)	series (i)

TABLE II
UNIPLANAR MMIC TRANSITION CIRCUIT

input transmission line \ output transmission line	coplanar waveguide	slotline	coupled slotline (even mode)
coplanar waveguide	—	(a)	(b)
slotline	(a)	—	(c)
coupled slotline (even mode)	(b)	(c)	—

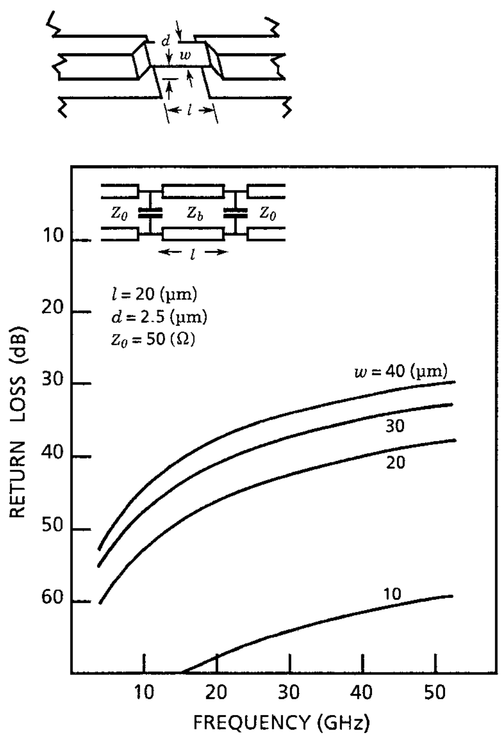
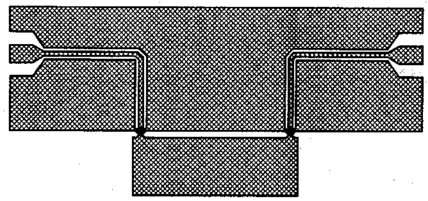


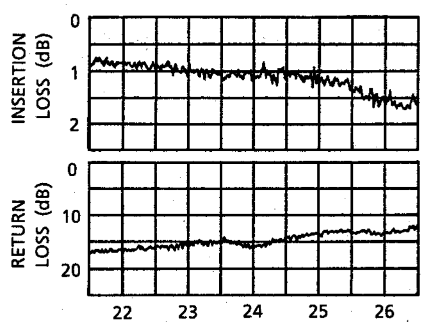
Fig. 3. Characteristic of bridged coplanar waveguide.

C. Air-Bridge Characteristics

Air bridges play an important role in uniplanar MMIC's. They connect coplanar waveguides with slotlines or coupled slotlines, as shown in Figs. 1 and 2. Air bridges may have a parasitic problem when the sizes involved are large. However, the precise MMIC fabrication process can control the width and height of the air bridges. One example of the theoretical transmission characteristic of the coplanar waveguide with an air bridge is shown in Fig. 3. The bridge is regarded as a microstrip line, and the microstrip-line design formula [13] is used in order to obtain its characteristic impedance and fringing capacitance. Fig. 3 shows that there is no discontinuity problem if the size of the air bridge is small.



(a)



(b)

Fig. 4. Characteristic of coplanar waveguide/slotline transition. (a) Circuit pattern. (b) Insertion loss (S_{21}) and return loss (S_{11}).

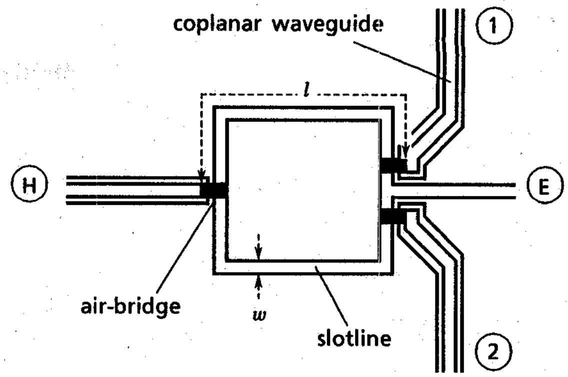
In order to confirm the theoretical prediction shown above, the coplanar waveguide/slotline transition is fabricated with the MMIC process. Fig. 4 shows the circuit pattern and experimental result of the coplanar waveguide/slotline transition. The insertion loss includes the transmission loss of two transitions and the conduction loss of the slotline (650 μm) and the coplanar waveguide (1000 μm). The experimental result of the transition circuit shows that air bridges do not interfere with the performance of uniplanar MMIC's.

III. Uniplanar Hybrid Circuits

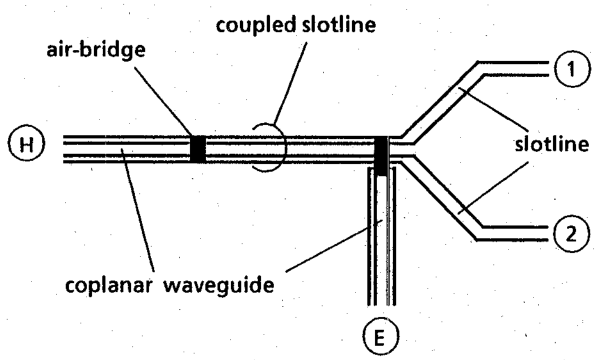
The 180° hybrid circuit (hybrid ring [14], magic T [6]) and the 90° hybrid circuit (branch line [15], coupled line [16]) are important passive devices in microwave circuits. New circuit configurations of the magic T and the branch-line coupler are proposed using the uniplanar MMIC technique. The T junctions and transitions described in Section II are successfully utilized to produce these circuits.

A. Magic T

Three circuit configurations are proposed and shown in Fig. 5. Ports Ⓔ and Ⓗ correspond to the E and H arms of the conventional waveguide magic T, respectively. The isolation between ports Ⓔ and Ⓗ is achieved by the difference of the balanced and unbalanced line characteristics (Fig. 5(a)), and the noncoupling characteristics of the coupled-slotline orthogonal modes [17] (Fig. 5(b) and (c)). All output transmission lines of the coupled-slotline-type magic T shown in Fig. 5(c) are composed of coplanar



(a)



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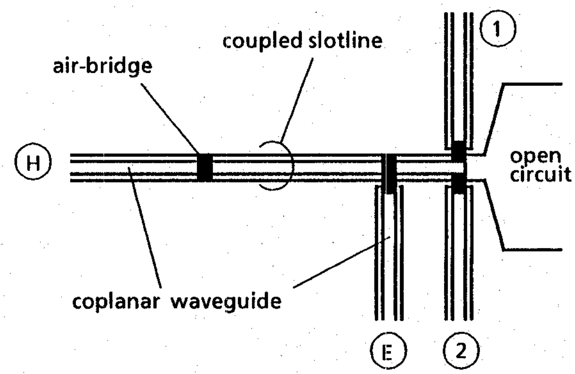

(c)

Fig. 5. Circuit configurations of uniplanar MMIC magic T's. (a) Slotline-type magic T. (b) Coupled-slotline-type magic T with slotline output transmission lines. (c) Coupled-slotline-type magic T with coplanar-waveguide output transmission lines.

waveguides. This makes it possible to produce small circuit patterns, because no coplanar waveguide/slotline transitions are needed to connect the coaxial connector.

The fundamental behavior of the slotline-type magic T can be understood by examining the electric-field direction in the slotline and coplanar waveguide. Fig. 6 gives a schematic explanation of the circuit behavior. In this figure, arrows represent the schematic expression of the electric field in those lines. Fig. 6(a) shows the in-phase dividing performance. The input signal fed to port Ⓗ propagates through the coplanar waveguide, and is then converted to the slotline by the coplanar waveguide/slotline junction. After propagation through the slotline, the signal is again converted to the coplanar waveguide, and

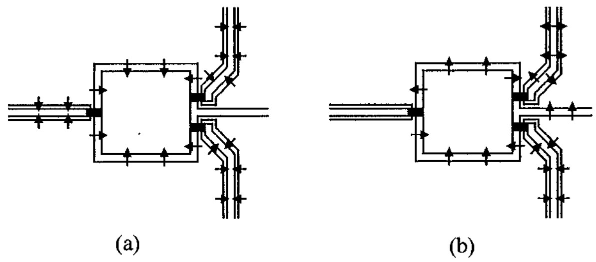

Fig. 6. Schematic fundamental behavior of the magic T. (a) In-phase excitation. (b) Out-of-phase excitation.

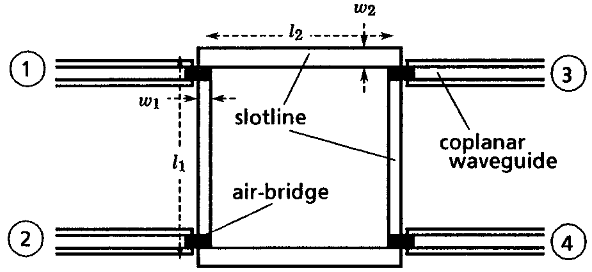

Fig. 7. Circuit configuration of uniplanar MMIC branch-line coupler.

in-phase output signals are obtained from each coplanar waveguide.

The out-of-phase dividing performance is shown in Fig. 6(b). The input signal fed to port Ⓔ propagates along the slotline. After propagation through the slotline T junction, the signal is converted to the coplanar waveguide, and out-of-phase output signals are obtained from each coplanar waveguide. The signal does not appear at the port Ⓗ, because the signal which propagates through the slotline is canceled at the coplanar waveguide/slotline T junction.

The behavior of the other magic T is also explained with the idea of the electric-field schema. Since the difference between Fig. 5(a), (b), and (c) is only in the use of the coplanar waveguide/coupled slotline T junction, a detailed explanation of their behavior is not described in this paper.

B. Branch-Line Coupler

The configuration of the uniplanar branch-line coupler is shown in Fig. 7. All branch lines are composed of slotlines and are excited by the coplanar waveguides through the air bridges. The characteristic impedance of each branch line is determined from the conventional design formula [15]. The input signal fed to port ① is divided into ports ② and ④ with the same amplitude and a phase difference of 90°, while port ③ is isolated.

C. Experimental Results

The magic T and the branch-line coupler are fabricated on a 450-μm-thick semi-insulating GaAs substrate using the conventional MMIC process. The bottom side of the substrate is not metallized. The width and height of the air bridge are determined according to the theoretical results shown in Fig. 3.

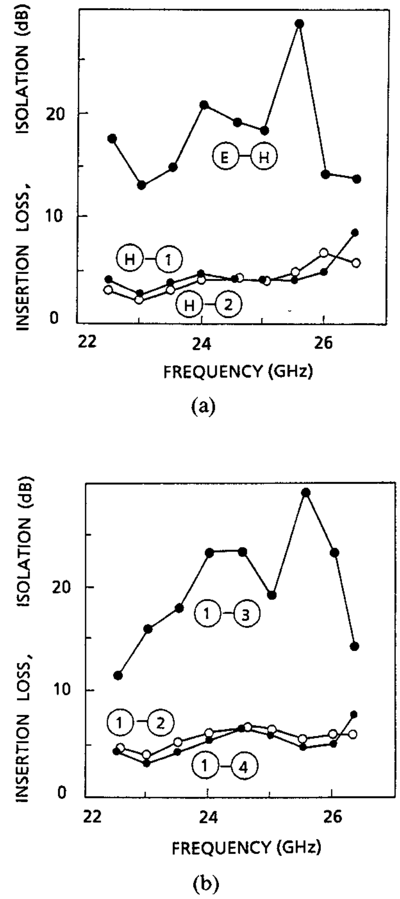

Fig. 8. Measured performance of uniplanar MMIC hybrid circuits. (a) Magic T ($w = 80$ μm, $l = 1.3$ mm). (b) Branch-line coupler ($w = 10$ μm, $w_2 = 45$ μm, $l_1 = 1.19$ mm, $l_2 = 1.22$ mm).

The measured performance is shown in Fig. 8. Fig. 8(a) shows the experimental results of the magic T (Fig. 5(a)). The total insertion loss between ports Ⓗ and ① or Ⓗ and ② is less than 5 dB in the frequency range of 22.5–25.5 GHz. The insertion loss includes the intrinsic hybrid circuit loss (3 dB), the conduction loss of the transmission lines, and the T junction and transition-circuit loss. The isolation is greater than 15 dB over a bandwidth of 2 GHz. This can be attributed to an imbalance in the terminated impedance at ports ① and ②.

The experimental data of the branch-line coupler (Fig. 7) are shown in Fig. 8(b). The total insertion loss between ports ① and ② or ports ① and ④ is less than 6 dB from 22.5 to 25.5 GHz. The increase in insertion loss is attributed to the conduction loss of the branch-line slotline, since the slot width of the branch line is very narrow (10 μm spacing). The isolation between ports ① and ③ is greater than 15 dB over a bandwidth of 3 GHz. Its bandwidth is limited by the quarter-wavelength branch-line slotline. As a result, the fundamental behavior of the magic T and the branch-line coupler using uniplanar MMIC techniques has been confirmed by measurements at *K*-band. These results also show that the use of an air-bridge structure does not interfere with circuit performance up to the 26-GHz band and may allow development of various circuits at high frequencies.

IV. Conclusions

A new uniplanar circuit configuration for MMIC's has been proposed. It uses coplanar waveguides and slotlines on one side of the substrate. These transmission lines are connected by air bridges. The uniplanar MMIC structure is fabricated by the conventional MMIC process, and the air bridges used in various junctions and transition circuits can be fabricated precisely. Novel hybrid circuits such as the magic T and the branch-line coupler have been fabricated at *K*-band and good performance has been achieved. These uniplanar MMIC's need no via holes for grounding. This makes it possible to apply the new structure to FET active circuits. The uniplanar MMIC proposed in this paper is expected to have wide applications at millimeter-wave band. It is useful in constructing such FET circuits as amplifiers, frequency converters, and phase shifters.

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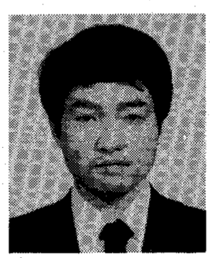

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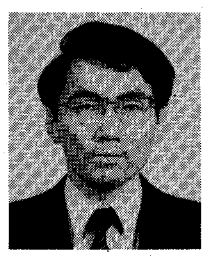

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