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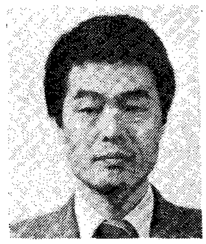

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A 26-GHz Band Integrated Circuit of a Double-Balanced Mixer and Circulators

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***Abstract* —Integration of a double-balanced mixer and ferrite-disk type circulators have been successfully achieved in the 26-GHz band. The total single-sideband noise figure of the integrated circuit, composed of a mixer and two circulators, is 8.5 dB, including the noise contribution from an IF amplifier. The double-balanced mixer is composed of microstrip lines, slot lines, coupled slot lines, coplanar lines, Au wires, and four beam lead Schottky-barrier diodes. The minimum conversion loss of the mixer is 5.3 dB at a signal frequency of 25.4 GHz. Isolation between RF and LO ports is greater than 30 dB. The ferrite-disk type circulator is produced by a newly developed precise machining technique. The minimum insertion loss of the circulator is 0.45 dB, and the isolation is greater than 20 dB. The integrated circuit with the ferrite-disk type circulators will be extended to the millimeter-wave band.**

I. Introduction

RECENTLY, microwave integrated circuits (MIC) have been used to produce various circuits, i.e., oscillators [1], mixers [2], [3], modulators [4], [5], and circulators [6]–[11]. Moreover, MIC transmitters and receivers can be fabricated by combinations of these circuits [12], [13].

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MIC balanced mixers have been constructed by combinations of microstrip lines and slot lines at millimeter-wave band [14], [15]. A new structure for the double-balanced mixer, that is suitable for high frequency band, has been produced using combinations of microstrip lines, slot lines and coupled slot lines [16], [17]. However, since the mixer uses two plated through holes in the substrate to connect microstrip lines and slot lines, and since the insertion loss increases and the isolation decreases due to these holes, the realizable frequency of the mixer is still limited to the 20-GHz band.

In this paper, a new configuration of a double-balanced mixer has been proposed for use at high frequency bands. Two gold (Au) wires are used to construct an intermediate-frequency (IF) circuit instead of two cylindrical conductors in the substrate. Thereby the insertion loss and the isolation of the mixer has been improved at frequencies above the 20-GHz band.

MIC circulators take an important part in transmitters and receivers. Circulators are used as isolators, combiners, and input/output terminals for reflection-type amplifiers. MIC circulators are divided into two different forms. One form consists of a ferrite disk embedded into a dielectric substrate (referred to as the "ferrite-disk" type) [7], while the other uses an all-ferrite substrate [8]. Generally, most microwave integrated circuits are fabricated on a dielectric

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substrate, such as an alumina or fused quartz. When the all-ferrite type circulator is used in transmitters and receivers, there are some problems in obtaining good impedance matching at interfaces with dielectric substrates. Since the relative permittivity of the ferrite is different from that of usually used dielectric substrates (i.e., ferrite ($\epsilon_r = 13$), alumina ($\epsilon_r = 9.6$), fused quartz ($\epsilon_r = 3.8$)), the microstrip line width is different for equal characteristic impedances. Therefore, the connection of ferrite and dielectric substrate is inevitably accompanied by reflection loss. Moreover, microstrip lines have greater loss on ferrite than on dielectric substrates. These excess losses increase with frequency.

On the other hand, in case of the ferrite-disk type circulator, reflection and thermal loss of the connections solely depend upon its dimensional precision. Furthermore, the circuit patterns with different functions, e.g., mixer, oscillator, etc., can be fabricated on one dielectric substrate by one photolithographic procedure. Consequently, one can reduce the degradation due to connections between substrates, which are inevitable for MIC with all-ferrite type circulators.

Ferrite-disk type circulators have been produced by a new precise machining method developed by the authors. For MIC circulators, a precise machining technique is required for high frequencies. The dimensional imperfection (mainly the gap between the ferrite and the hole, the roughness of the sidewall, and the roundness) have been found to cause an excess insertion loss (return loss and thermal loss).

First, mixers and circulators have been made separately at 26-GHz band, in order to investigate individual electrical performance of each device. Secondly, the integrated circuit of a double-balanced mixer and two ferrite-disk type circulators have been made on a single alumina substrate at 26-GHz band. This type of integrated circuit showed a better performance than a gold-ribbon-connected assembly.

II. Double-Balanced Mixer

The configuration of the proposed double-balanced mixer is shown in Fig. 1. The dimensions of the circuit pattern are also given. In the figure, solid lines indicate microstrip lines on the substrate, while dotted lines indicate slot lines, coupled slot lines, and coplanar lines on the reverse side of the substrate. Two Au wires with a diameter of 50 μm are used to connect slot lines and coplanar lines. Ⓡ, Ⓛ, and Ⓘ denote the signal frequency (RF) input port, the LO input port, and the IF output port, respectively. The circuit consists of an MIC magic-T (180-degree hybrid) and a diode circuit. Through the magic-T, the RF signal and the LO signal are supplied to two pairs of diodes, 180-degree out-of-phase and in phase, respectively. The IF signal is derived from port Ⓘ composed of a coplanar line. The image signal appears at port Ⓡ, and is matched. The configuration of the magic-T and the diode circuit in Fig. 1 is the same as the mixer previously described [16]. Four diodes in the mixer are beam-lead Schottky-barrier diodes [18].

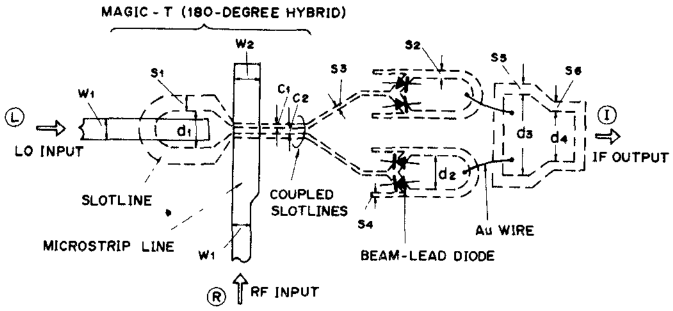


Fig. 1. Configuration of double-balanced mixer. Solid lines show microstrip lines on the substrate, dotted lines show slot lines and coupled slot lines on the reverse side of the substrate. $w_1 = 0.3$ mm, $w_2 = 0.45$ mm, $S_1 = 0.26$ mm, $S_2 = 0.13$ mm, $S_3 = 0.03$ mm, $S_4 = 0.06$ mm, $S_5 = 0.2$ mm, $S_6 = 0.16$ mm, $C_1 = 0.04$ mm, $C_2 = 0.05$ mm, $d_1 = 0.6$ mm, $d_2 = 0.6$ mm, $d_3 = 1.8$ mm, $d_4 = 1$ mm.

The circuit configuration shown in Fig. 1 has the following advantages.

1) The circuit for the IF signal is easily fabricated by Au wires instead of plated through-holes in the substrate.

2) The conversion loss and the isolation are improved by wire bonding.

3) The mixer can be well extended to the millimeter-wave band by reducing the diameter of the Au wire.

The circuit pattern is made on a 0.3-mm thick alumina substrate ($\epsilon_r = 9.6$) by a usual photolithographic technique. A 500-Å thick nickel-chromium and 6000-Å thick gold layer are deposited on the alumina substrate by vacuum evaporation. The thickness of a gold on the microstrip lines and slot lines is increased to about 4 μm by electroplating.

Diodes used here, typically, have a series resistance of 0.45 Ω ($I_f = 30$ mA at dc), a junction capacitance of 0.12 pF at zero bias ($f = 1$ MHz), a stray capacitance of 0.045 pF, and a breakdown voltage of 8 V. The size of the beam-lead diode is about 750×220 μm^2. Matching between input/output ports and diodes are accomplished by slot lines.

The experimental results of the mixer are shown in Figs. 2, 3, and 4. In the experiment, the RF signal and LO power are fed to the waveguide-to-microstrip transitions constructed with ridged waveguide [19]. The IF signal port is connected to a coaxial connector.

The measured conversion loss of the mixer is presented in Fig. 2. The LO signal frequency is 26 GHz. The IF is varied in the range from 0.05 to 1 GHz. The minimum conversion loss is 5.3 dB at an intermediate frequency of 0.2 GHz. The variation of the conversion loss is 0.5 dB over the IF bandwidth of 1 GHz.

Fig. 3 shows the conversion loss for a fixed intermediate frequency of 140 MHz. The minimum conversion loss is 5.3 dB at a signal frequency of 25.4 GHz. The frequency response of the conversion loss is very flat. The loss variation is less than ±0.3 dB for a frequency range of 25–26 GHz. In Figs. 2 and 3 the LO input power is fixed at 15 dBm.

The isolation characteristic between ports Ⓛ and Ⓡ is shown in Fig. 4. The isolation of the mixer is greater than 30 dB over a range of 25–26 GHz. The return loss of the

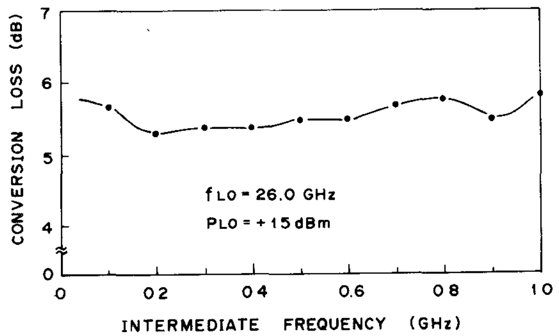


Fig. 2. Conversion loss of double-balanced mixer, with a fixed local-oscillator power of 15 dBm and a local frequency of 26 GHz.

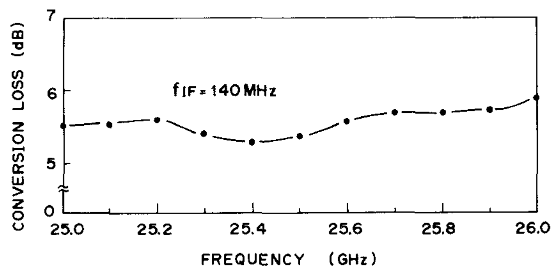


Fig. 3. Conversion loss with an intermediate frequency of 140 MHz and a local power of 15 dBm.

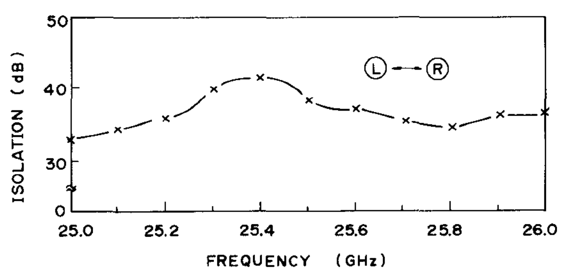


Fig. 4. Isolation characteristic of double-balanced mixer.

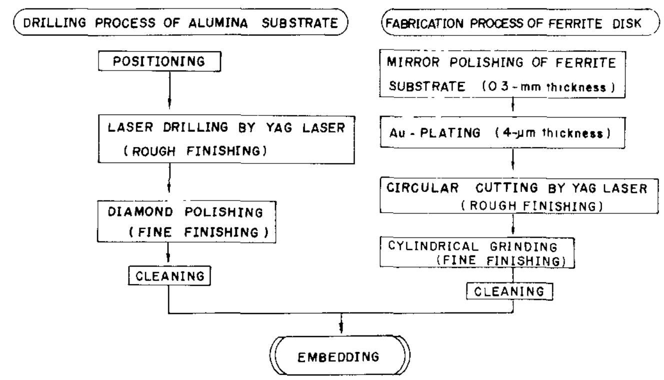


Fig. 5. Fabrication process for the ferrite-disk type circulator.

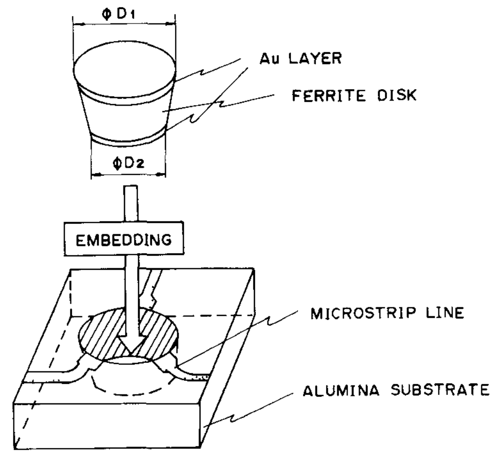


Fig. 6. Ferrite disk embedding method. $\Delta D = \phi D_1 - \phi D_2$: diameter difference of both surfaces (ferrite disk and hole in alumina substrate).

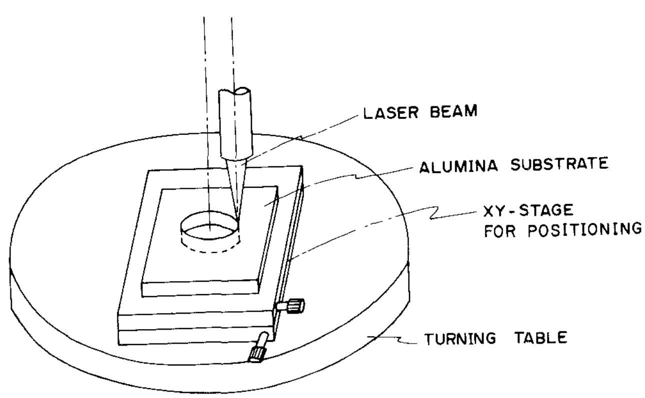


Fig. 7. Laser drilling of the alumina substrate.

RF signal port is greater than 12 dB. Consequently, the double-balanced mixer described here has good isolation and low conversion loss due to the effective combination of microstrip lines, slot lines, coupled slot lines, coplanar lines, and Au wires.

III. Ferrite-Disk Type Circulator

A. Precise Machining Technique

Since the excess loss of the ferrite-disk type circulator is mainly caused by the dimensional imperfection (gap between the ferrite and the hole, roughness of the side wall, and roundness), the realizable frequency depends upon its dimensional precision. The precise machining of an alumina substrate and a ferrite disk is described in the following.

Fig. 5 shows the flow chart of the fabrication process. The fabrication consists of two processes, i.e., the drilling of the alumina substrate and the fabrication of the ferrite disk. The essential parts of the two processes are i) the precise machining of cylindrical holes in the alumina substrate and ferrite disks, and ii) finishing the holes and disks to have a slight taper in cross section, as shown in Fig. 6. Therefore the ferrite disk fits tightly and perfectly into the hole in the alumina substrate without an adhesive.

Drilling of alumina substrate consists of laser drilling and diamond polishing. A YAG laser is used to avoid machining variation when drilling the substrate. Fig. 7

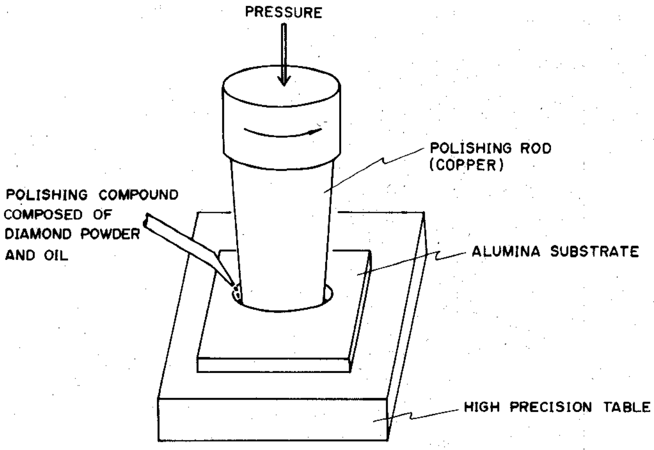


Fig. 8. Diamond polishing of the hole in the alumina substrate.

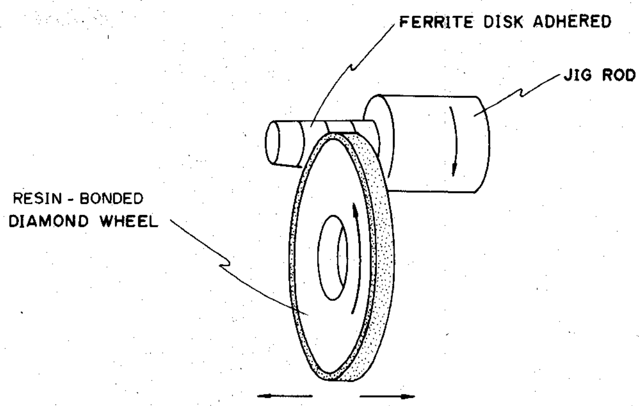


Fig. 10. Cylindrical grinding of the ferrite disk.

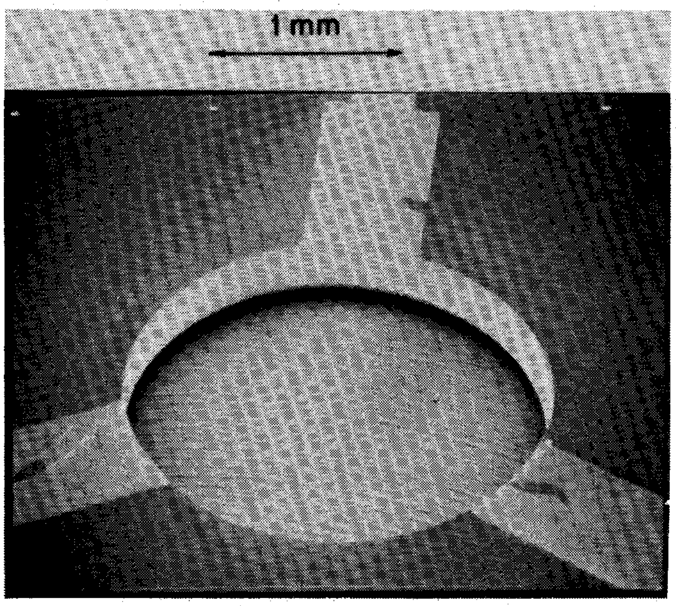


Fig. 9. Scanning electron micrograph of a hole in the alumina substrate produced by laser drilling and diamond polishing.

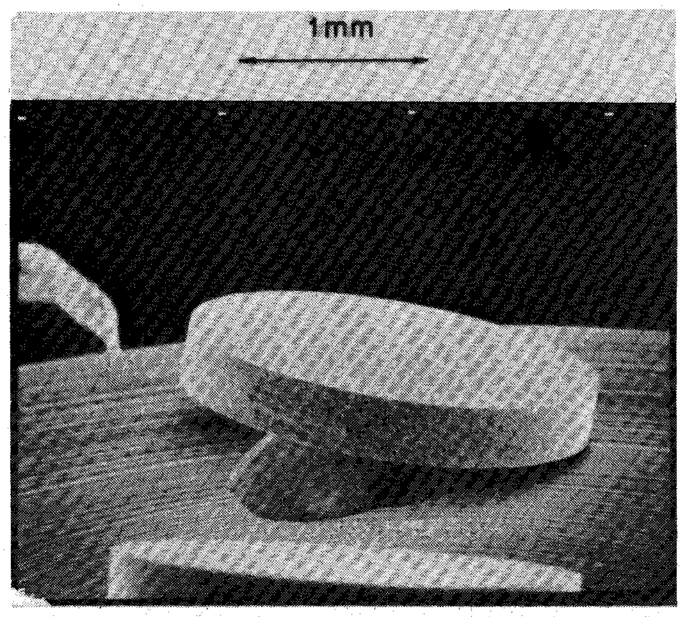


Fig. 11. Scanning electron micrograph of the ferrite disk produced by laser drilling and cylindrical grinding.

shows the schematic diagram of the laser drilling. The positioning accuracy of the holes is of the order of several microns. The thermally damaged region of the substrate is about 40 μm, judged from the discolored part of the substrate.

Fig. 8 shows the schematic diagram of the diamond polishing. The inside wall of the hole is polished by a high-speed rotating tapered rod, supplied with a polishing compound composed of diamond powder and oil. The polishing rod consists of copper and has about a 1° taper. The hole is polished by at least 40 μm to remove the thermally damaged region. By diamond polishing, the difference of diameters ΔD shown in Fig. 6 is made to about 5 μm. The roughness of the inside wall is less than 0.1 μm. Fig. 9 shows a scanning electron micrograph of the hole in the alumina substrate thus fabricated. There can be found no chipping and cracking of the substrate.

The ferrite disk is produced from the ferrite substrate, that is already mirror polished and electrically plated. The fabrication process consists of laser drilling and cylindrical grinding. A YAG laser is also used to cut the ferrite disk from the ferrite substrate. The ferrite disk is cut slightly larger (about 40 μm) than the desired value, because of the thermally damaged region of the ferrite after cutting.

Fig. 10 shows the cylindrical grinding of the side wall of the ferrite disk. Several ferrite disks are piled onto a jig rod, and are cylindrically ground by a resin-bonded diamond wheel to a difference in diameter $\Delta D \leqslant 5$ μm. After cylindrical grinding, these disks are separated and washed by a solvent. There are neither damages of the Au layers nor chippings of the ferrite material. Fig. 11 shows a scanning electron micrograph of the ferrite disk produced by the machining technique described above.

The dimensional precisions realized are summarized in

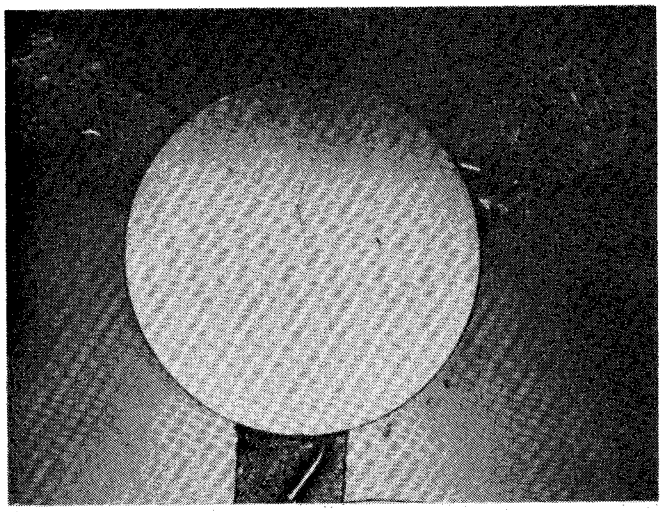


Fig. 12. Photograph of the ferrite disk embedded into the alumina substrate.

TABLE I
REALIZED VALUES OF FABRICATED CIRCULATOR

	Hole in the alumina substrate		Ferrite disk		Embedding
	Face	Back side	Face	Back side	
Diameter (mm)	2.189	2.186	2.186	2.182	———
Roundness*	Less than 2 μm		Less than 2 μm		———
Diameter difference ΔD	Less than 5 μm		Less than 5 μm		———
Roughness in side wall	Less than 0.1 μm		Less than 0.1 μm		———
Positioning accuracy	Less than 15 μm		———		———
Gap	———		———		Less than 3 μm
Step**	———		———		Less than 10 μm

* Difference between maximum and minimum diameters.
** Difference of levels of two surfaces (ferrite surface and substrate surface).

Table I. Highly precise machining of alumina and ferrite has been achieved. Fig. 12 shows a photograph of the ferrite disk embedded into the hole of the alumina substrate. The gap is estimated to be less than 3 μm, and the fitting of the disk and hole is tight and perfect.

B. Experimental Results of Circulators

The basic theory used in the design of these microstrip circulators is that derived by Fay and Comstock [20]. The type of operation is below resonance, and the mode of the resonant cavity is the lowest order mode TM_{110}. The magnetic biasing field is applied in the direction of the axis of the ferrite disk. The diameter of the resonant cavity is calculated using operating frequency, permeability, and permittivity of the ferrite medium. Table II shows the design parameters of microstrip circulator produced here.

Microstrip lines for the input and output transmission lines of the circulators are fabricated by a photolithographic technique on a 0.3-mm thick alumina substrate with a relative permittivity of 9.6. The microstrip circulator is mounted in a test housing, including waveguide-to-microstrip transitions that are constructed with ridged waveguide [19]. The biasing magnetic field is supplied by a permanent magnet[1] located under the substrate.

Fig. 13 shows the electrical performance of the fabricated circulator. The insertion loss does not include the loss of the waveguide-to-microstrip transitions. The return loss is greater than 20 dB over the range of 24–28.5 GHz, and the isolation is greater than 20 dB over the range of 24–28.5 GHz, and the isolation is greater than 20 dB from 24.5 to 30 GHz. A good impedance match and isolation are realized over a wide band. The insertion loss is less than 0.6 dB over the range from 23.5 to 28.5 GHz, particularly less than 0.45 dB from 25.5 to 26.5 GHz. The insertion loss is attributed to conductor loss in the conductor on the ferrite disk, and dielectric and magnetic loss in the ferrite disk.

To estimate the loss due to the machining imperfection, microstrip circulators without polishing have been produced. The hole in the alumina substrate is fabricated by a diamond drilling. The roughness of the side wall of the hole and the disk is 20 μm peak-to-peak, and the average gap is on the order of 30 μm. The return loss and isolation

[1]Samarium cobalt magnet of Tohoku Metal Industry's Limit.

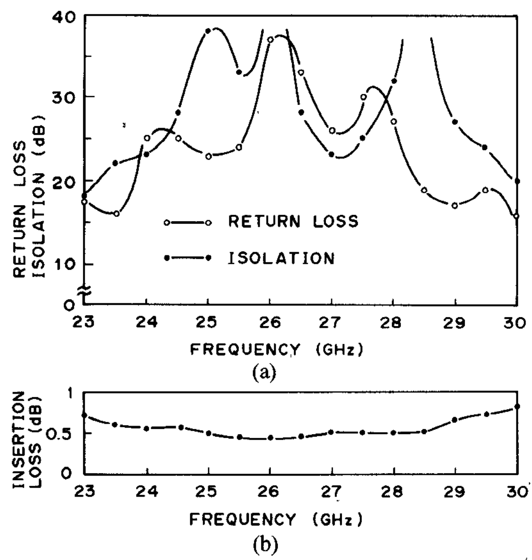


Fig. 13. Performance of microstrip circulator produced by precise machining technique. (a) Return loss and isolation. (b) Insertion loss.

TABLE II
DESIGN PARAMETERS OF CIRCULATOR

Quantity		Values
Center frequency	f_0	26 GHz
Dielectric substrate		HA995*
Thickness of substrate	d_s	0.3 mm
Ferrite material		Ni-Zn 1500M**
Thickness of ferrite	d_f	0.3 mm
Saturation magnetization	$4\pi M_s$	5000 Gauss
Relative permittivity	ε_r	13
Magnetic biasing field	H_{DC}	3000 Gauss
Polder tensor ratio	κ/μ	0.52
Loaded Q	Q_L	1.36
Disk radius	R	1.09 mm
Conductance of disk resonator	G_R	0.081 S
Transformer admittance	Y_T	0.04 S

* NGK Company.
** Tohoku Metal Industry's Limit.

is less than 20 dB, and the insertion loss is greater than 1 dB, hence much worse than that shown in Fig. 13.

These results show that the electrical performance closely depends upon the roughness of the interface between the disk and the hole. Our precise machining technique has shown to be effective and suitable for production of the ferrite-disk type circulator at high frequency band up to the millimeter-wave band.

IV. INTEGRATION OF MIXER AND CIRCULATORS

The circuit configuration of the integrated circuit composed of a double-balanced mixer and two ferrite-disk type circulators is shown in Fig. 14. In this figure, solid lines indicate microstrip lines on the substrate, while dotted lines indicate slot lines, coupled slot lines, and coplanar lines on the reverse side of the substrate. Two ferrite disks depicted by hatching are embedded into the cylindrical holes in the dielectric substrate. Since two circulators work

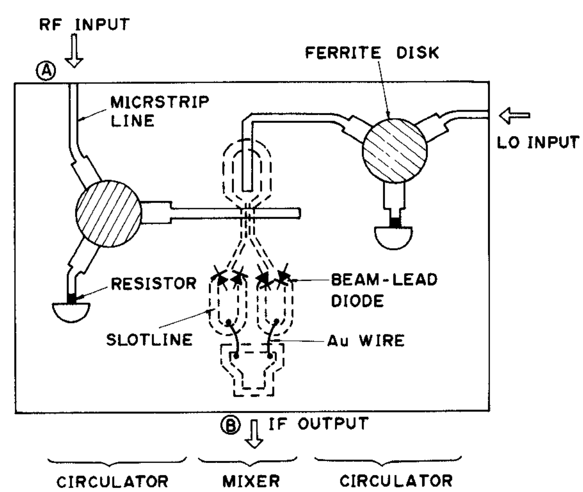
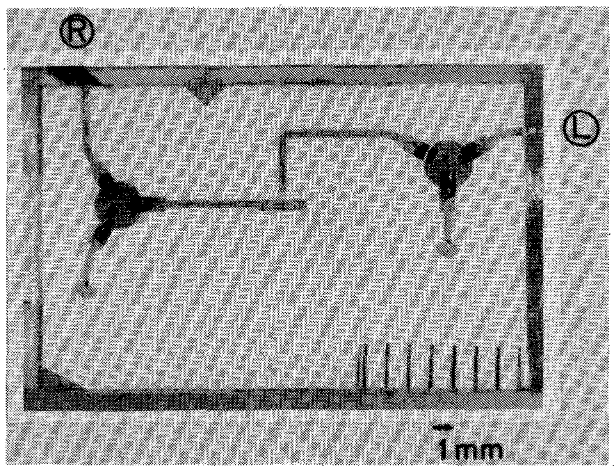
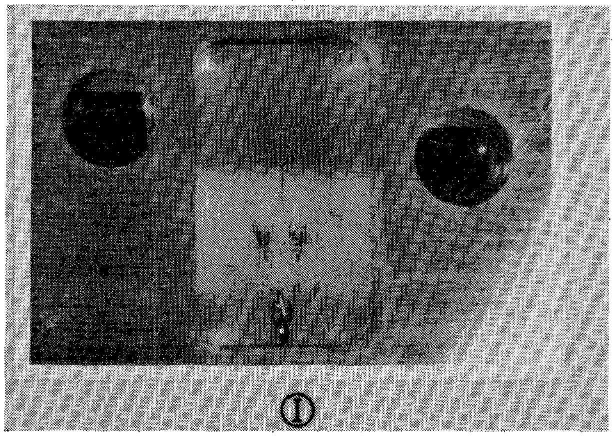


Fig. 14. Integration of a double-balanced mixer and two circulators. Solid lines show microstrip lines on the substrate, dotted lines show slot lines and coupled slot lines on the reverse side of the substrate.



(a)



(b)

Fig. 15. Photographs of integrated circuit of a mixer and two circulators. (a) Microstrip line pattern on the substrate. (b) Slot-line pattern on the reverse surface.

TABLE III
CHARACTERISTICS OF INTEGRATED CIRCUIT OF A MIXER AND TWO CIRCULATORS, WITH AN INTERMEDIATE FREQUENCY OF 140 MHz AND A LOCAL-OSCILLATOR INPUT POWER LEVEL OF 16 dBm

Number	LO frequency (GHz)	Conversion loss* (dB)	Total SSB noise figure** (dB)
1	25.14	5.9	9.0
2	25.14	6.0	8.9
3	26.14	5.9	8.5

* Conversion loss includes the insertion loss of a circulator (from Ⓐ to Ⓑ in Fig.14).
** The noise figure of the IF amplifier is 1.4 dB.

as isolators, one of three ports is terminated by a matched load. The matched load is realized by tantalum nitride (Ta_2N) resistor sputtered on the dielectric substrate. The three-layer metal system, Ta_2N–NiCr–Au, is used on one side while the two-layer metal system, NiCr–Au, is used on the reverse side. The sheet resistance of the tantalum nitride is 35 Ω/square.

The double-balanced mixer and two ferrite-disk type circulators shown in Fig. 14 are fabricated on a 0.3-mm thick and 14×22-mm^2 area alumina substrate. Fig. 15 shows photographs of the circuit pattern mounted in a test housing. Fig. 15(a) shows the pattern of the microstrip line on the substrate and the ferrite disk, and Fig. 15(b) the pattern of the slot line and coupled slot lines, on the reverse surface of the substrate. Two cylindrical holes in the test housing shown in Fig. 15(b) are holes for embedding permanent magnets.

The characteristics of the integrated circuit of a mixer and two circulators are summarized in Table III. Three patterns are produced and measured at the LO frequency of 25.14 and 26.14 GHz. The conversion loss includes the insertion loss of a circulator. The total single-sideband noise figure shown in Table III is measured by a noise tube and noise figure meter. The noise figure of the 140-MHz IF amplifier is 1.4 dB. The measurement system includes a waveguide circulator, waveguide bandpass filter, and a transition of waveguide to microstrip line. These losses are subtracted from noise figure in Table III.

To estimate the excess loss of the interconnections of ferrite substrate and alumina substrate, a mixer circuit including two all-ferrite type circulators has been constructed. The insertion loss of the circulator is 0.8 dB, and the measured conversion loss is 6.5 dB. By integrating on a single alumina substrate, a 0.6-dB improvement in the front-end single-sideband noise figure has been obtained.

V. CONCLUSION

Integration of a double-balanced mixer and two ferrite-disk type circulators has been successfully achieved at 26 GHz. A total single-sideband noise figure of 8.5 dB has been obtained.

The double-balanced mixer described here realizes low conversion loss and high isolation. The minimum conversion loss is 5.3 dB at a signal frequency of 25.4 GHz, and the isolation is greater than 30 dB over a 1-GHz bandwidth. The ferrite-disk type circulator is produced by a precise machining technique. The insertion loss of the circulator is less than 0.45 dB over a range of 25.5–26.5 GHz. The return loss and the isolation is greater than 20 dB over a 4-GHz bandwidth. The machining technique described here will be applied to produce circulators up to the millimeter-wave band.

The integrated circuit of mixer and circulators fabricated in this paper is useful to construct MIC receivers in radio transmission systems. This type of integration will offer compact, cheap, and high-efficiency receivers. Moreover, this circuit is considered to be applicable to the front end up to the millimeter-wave band.

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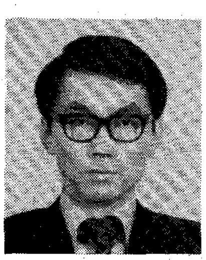

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