Slot-Coupled Directional Couplers Between Double-Sided Substrate Microstrip Lines and Their Applications

TOSHIAKI TANAKA, MEMBER, IEEE, KIKUO TSUNODA, MEMBER, IEEE, AND MASAYOSHI AIKAWA, MEMBER, IEEE

***Abstract*—This paper describes a slot-coupled microstrip directional coupler and its application to a planar multiport directional coupler (MDC). This slot-coupled microstrip directional coupler can be easily applied to tight coupling, such as 3 dB. A 4-port planar MDC fabricated by combining these couplers is described. Slot-coupled MDC's have many useful applications, such as beam-forming networks and multiport amplifiers.**

I. Introduction

COMPARED to waveguide circuits, microwave integrated circuits (MIC's) are more versatile because of their small size, light weight, and low cost. Recently, MIC's have been applied to such high-frequency circuits as millimeter-wave circuits and submillimeter-wave circuits [1]. A microstrip line is the basic transmission line for a conventional MIC. Many analyses of microstrip line characteristics have been reported [2]. Directional couplers using microstrip lines, such as quarter-wavelength parallel-coupled stripline directional couplers and branch line directional couplers, are common. However, parallel-coupled microstrip directional couplers cannot be easily used for tight couplings. Branch line directional couplers can be used for tight couplings, but need larger areas than parallel-coupled microstrip directional couplers.

This paper first proposes a simple design method for a slot-coupled directional coupler consisting of two microstrip lines which couple through a rectangular slot in a common ground plane [3]. The proposed slot-coupled directional coupler can be applied to both loose couplings (such as 10 dB) and tight couplings (such as 3 dB).

Next, the useful application of this coupler to a planar multiport directional coupler (MDC) is described. MDC's are very useful circuits. For example, beam-forming networks [4] and multiport amplifiers [5] can be constructed by mounting active circuits such as phase shifters and power amplifiers between two MDC's. MDC's are fabricated by combining directional couplers, but it is difficult to make planar MDC's using conventional directional couplers because of complicated wiring such as microstrip line crossovers. An effective planar configuration MDC can be easily made by combining slot-coupled directional couplers. A planar MDC is advantageous in view of its easy design and fabrication.

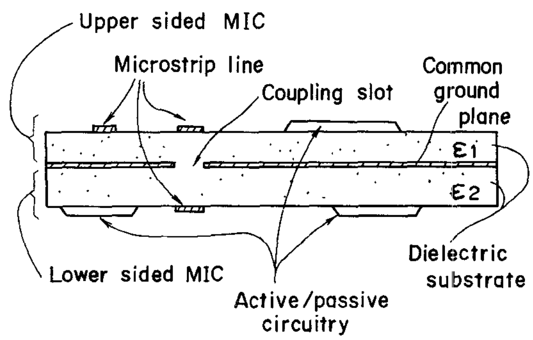


Fig. 1. Cross-sectional view of double-sided substrate MIC configuration.

II. Construction of a Slot-Coupled Directional Coupler

A cross-sectional view of a so-called double-sided substrate MIC is illustrated in Fig. 1. Its transmission lines and other circuit patterns lie on opposite sides of a common ground plane inserted between layers of dielectric material. Transmission lines on each side are shielded from those on the other side by the ground plane, and there is no interaction between them. The slot-coupled directional coupler is one of the elements of the double-sided substrate MIC.

A cutaway view of the slot-coupled directional coupler is illustrated in Fig. 2. The microstrip lines are coupled through a slot in the common ground plane. The coupling lengths of the slot and the coupling strip are both equal to a quarter of the midband wavelength. The operating principle of this slot-coupled directional coupler is essentially the same as that of a quarter-wavelength parallel-coupled stripline directional coupler.

Manuscript received April 6, 1988; revised July 15, 1988.
K. Tsunoda and M. Aikawa are with the ATR Optical and Radio Communications Research Laboratories, 2-1-61 Shiromi, Higashi-ku, Osaka, 540 Japan.
T. Tanaka was with the ATR Optical and Radio Communications Research Laboratories, Osaka, Japan. He is now with the NTT Network Systems Development Center, Tokyo, Japan.
IEEE Log Number 8823769.

0018-9480/88/1200-1752$01.00

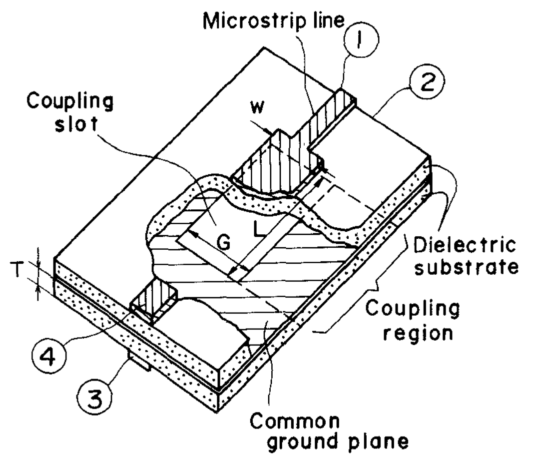


Fig. 2. Cutaway view of slot-coupled directional coupler.

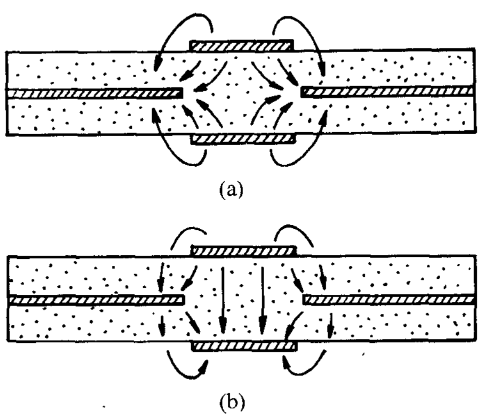


Fig. 3. Schematic expression for (a) even- and (b) odd-mode electric fields in the coupling region.

III. Design of the Slot-Coupled Directional Coupler

In designing the slot-coupled directional coupler, the even- and odd-mode characteristics in the coupling region must be evaluated. Fig. 3 gives a schematic expression of the even- and odd-mode electric fields. The wavelength and the characteristic impedance of each mode are calculated by quasi-TEM wave analysis. Using this method, the capacitance value per unit length must be calculated. To do this, the finite element method (FEM) is adopted. The wavelengths (λ_{ge} of the even mode, λ_{go} of the odd mode) and the characteristic impedances (Z_e of the even mode, Z_o of the odd mode) are calculated using the capacitance values per unit length (C_e of the even mode, C_o of the odd mode) as follows:

$$\lambda_{ge} = \lambda_0 \sqrt{\frac{C_{0e}}{C_e}} \qquad \lambda_{go} = \lambda_0 \sqrt{\frac{C_{0o}}{C_o}}$$

$$Z_e = \frac{1}{V_0\sqrt{C_{0e}C_e}} \qquad Z_o = \frac{1}{V_0\sqrt{C_{0o}C_o}}$$

where V_0 is velocity of light, $C_{0e}C_{0o}$ are capacitance values per unit length of the even and odd modes without dielectric material, and λ_0 is wavelength in free space.

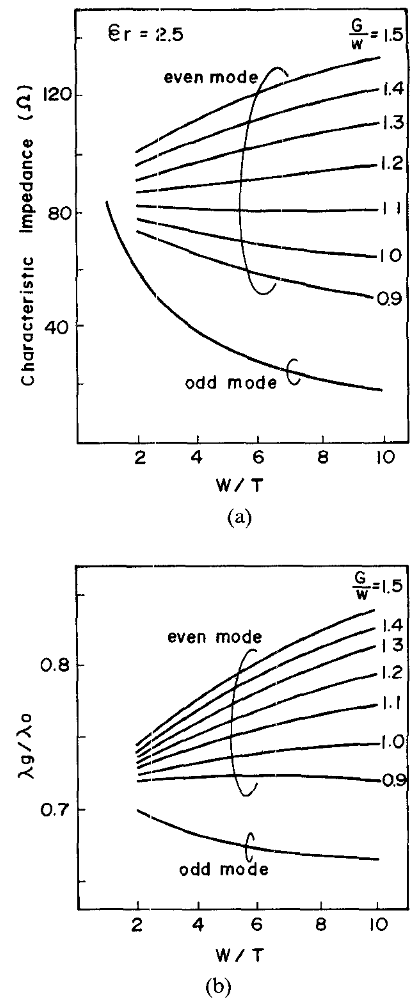


Fig. 4. (a) Characteristic impedance and (b) normalized wavelength of even and odd modes.

Fig. 4 shows the calculated characteristic impedances and normalized wavelengths for the even and odd modes for the case where the relative permittivity ϵ_r of dielectric material is 2.5. The coupling slot plane is an electric wall in the odd mode and a magnetic wall in the even mode. Because the odd-mode electromagnetic field is the same as that of the microstrip line, the odd-mode characteristic impedance is determined by the W/T ratio and ϵ_r, where W is the coupling strip width and T is the substrate thickness, and it is independent of the coupling slot width G.

The design procedure is as follows:

1) Calculate the even-mode characteristic impedance Z_e (Ω) and the odd-mode characteristic impedance Z_o (Ω) for the desired coupling C (dB) according to the following equations [6]:

$$C \text{ (dB)} = -20\log_{10}\left(\frac{Z_e - Z_o}{Z_e + Z_o}\right)$$

$$Z_0 \ (\Omega) = \sqrt{Z_e Z_o}$$

TABLE I
DESIGN VALUES OF SLOT-COUPLED DIRECTIONAL COUPLERS

Coupling [dB]	Characteristic Impedance [ohm]		Dimension [mm]		
	even-mode	odd-mode	W	G	L
3.0	120.5	20.7	7.3	10.2	36.4
6.0	86.7	28.8	4.8	5.6	35.6
10.0	69.4	36.0	3.5	3.4	35.1

Center frequency: 1.5 GHz.
Relative permittivity: 2.5.
Substrate thickness (T): 0.8 mm.

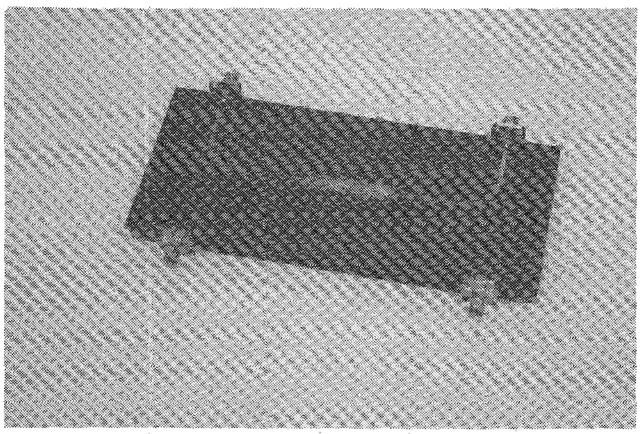


Fig. 5. Photograph of 3 dB slot-coupled directional coupler.

where Z_0 is transmission line characteristic impedance.

2) Determine the coupling strip width W corresponding to Z_o.
3) Determine the coupling slot width G corresponding to Z_e.
4) Determine the coupling length L, equal to the arithmetic mean of the even- and odd-mode quarter wavelengths:

$$L = \frac{\lambda_{ge} + \lambda_{go}}{8}.$$

IV. Performance of the Slot-Coupled Directional Coupler

Table I shows the design values of even- and odd-mode characteristic impedances and the coupling region dimensions of 3 dB, 6 dB, and 10 dB directional couplers. The values of W, G, and L are calculated at a center frequency of 1.5 GHz, where substrate thickness is 0.8 mm and the relative permittivity ϵ_r is 2.5. A photograph of a fabricated 3 dB coupler is shown in Fig. 5. Figs. 6 through 8 show the frequency performance of these directional couplers. Table II shows the measured results for coupling, return loss, and isolation obtained in the range of 1.2–1.8 GHz. For these couplers, more than 25 dB return loss and more than 28 dB isolation were obtained over the 1.2–1.8 GHz range, as shown in Figs. 6 through 8. The measured coupling results for these couplers closely matched the calculated results.

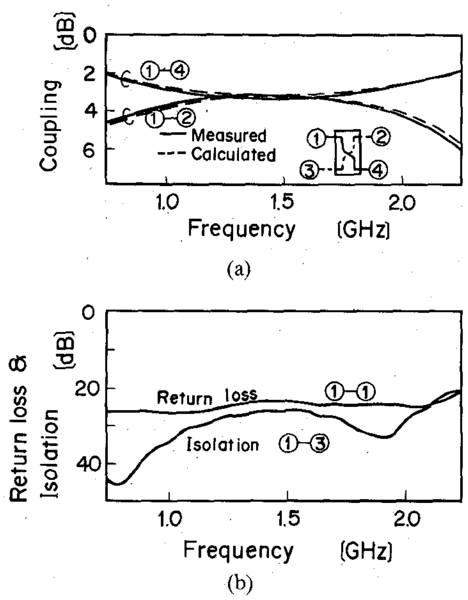


Fig. 6. Frequency characteristics of a 3 dB slot-coupled directional coupler. (a) Coupling. (b) Return loss and isolation.

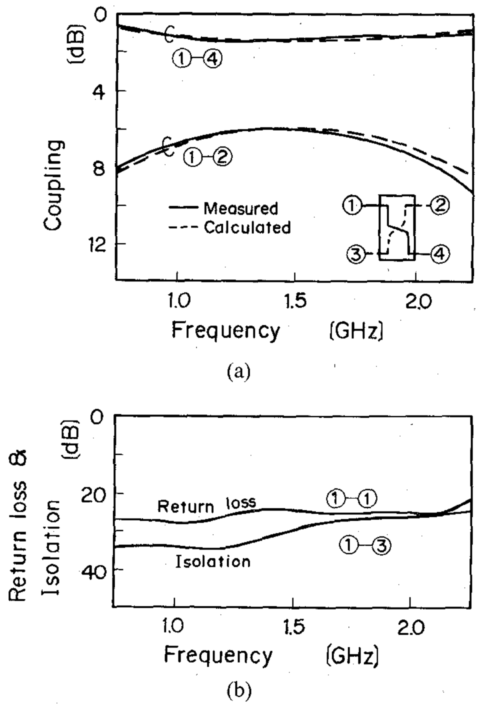
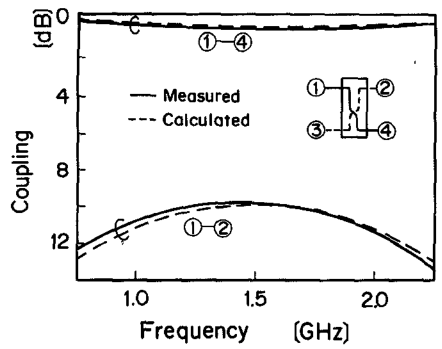


Fig. 7. Frequency characteristics of a 6 dB slot-coupled directional coupler. (a) Coupling. (b) Return loss and isolation.

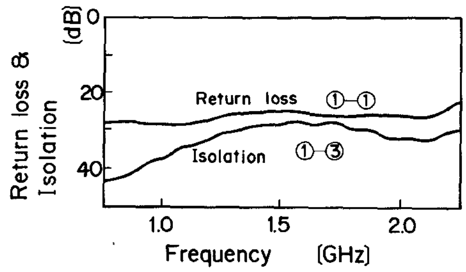
V. Application for MDC's

A. Construction of MDC's

A 2^n-port MDC ($n = 1, 2, \cdots$) can be constructed by using $n2^{n-1}$ directional couplers [7], where 2^n is the number of input ports or outputs ports. A typical MDC configuration is shown in Fig. 9. To construct a 2^n-port MDC, two 2^{n-1}-port MDC's are set parallel at the input port, and then the output ports of a 2^{n-1}-port MDC are coupled through a 2-port MDC with those of another 2^{n-1}-port MDC.

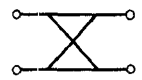


(a)

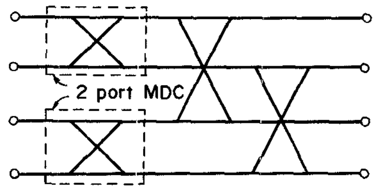


(b)

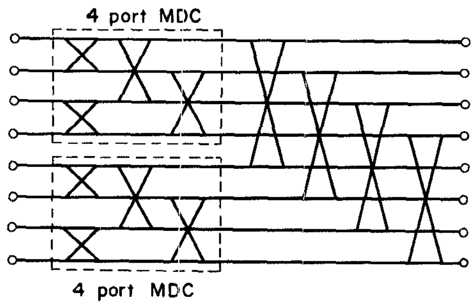
Fig. 8. Frequency characteristics of a 10 dB slot-coupled directional coupler. (a) Coupling. (b) Return loss and isolation.



(a)



(b)



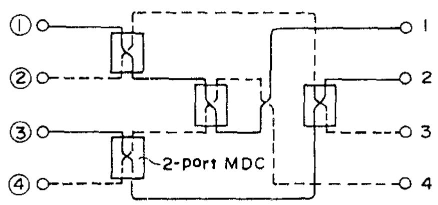
(c)

Fig. 9. Typical MDC configuration. (a) 2-port MDC. (b) 4-port MDC. (c) 8-port MDC.

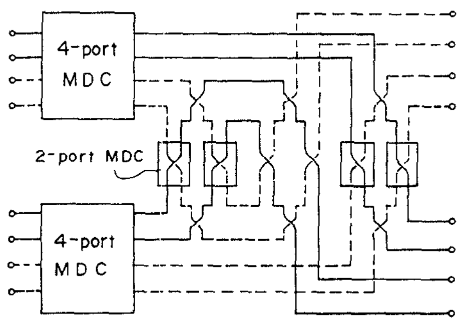
TABLE II
MEASURED RESULTS OF SLOT-COUPLED DIRECTIONAL COUPLERS

Coupling [dB] (Design)	Measured results [dB]		
	Coupling	Return loss	Isolation
3.0	3.2±0.2	25 min.	28 min.
6.0	6.2±0.2	25 min.	28 min.
10.0	10.2±0.2	25 min.	28 min.

Frequency range: 1.2–1.8 GHz.



(a)



(b)

Fig. 10. (a) 4-port and (b) 8-port MDC configurations.

It is difficult to make an effective planar configuration MDC with conventional microstrip directional couplers because microstrip line crossovers are needed to connect the ports. Some undesirable effects, such as interactions and transmission phase error, occur at microstrip line crossovers.

A combination of slot-coupled directional couplers, however, makes it possible to construct a planar 2^n-port MDC without microstrip line crossovers. Fig. 10 shows examples of 4-port and 8-port planar MDC configurations using slot-coupled directional couplers. Solid lines show the microstrip lines on one side and broken lines show microstrip lines on the other side. Microstrip line crossovers on the same plane can be avoided with this configuration.

Fig. 11 shows the general configuration of a 2^n-port MDC. It contains two 2^{n-1}-port MDC's (#1 and #2). Half of the output ports of #1 and #2 are on one side and half are on the other side. To construct a 2^n-port MDC, each output port on one side of #1 MDC is coupled to a corresponding output port on the other side of #2 MDC. As shown in Fig. 11, these couplings are made using slot-coupled directional couplers without microstrip line crossovers. Moreover, it is possible to connect transmission lines from the coupling regions to the 2^n-port MDC's output port positions without microstrip line crossovers on the same plane.

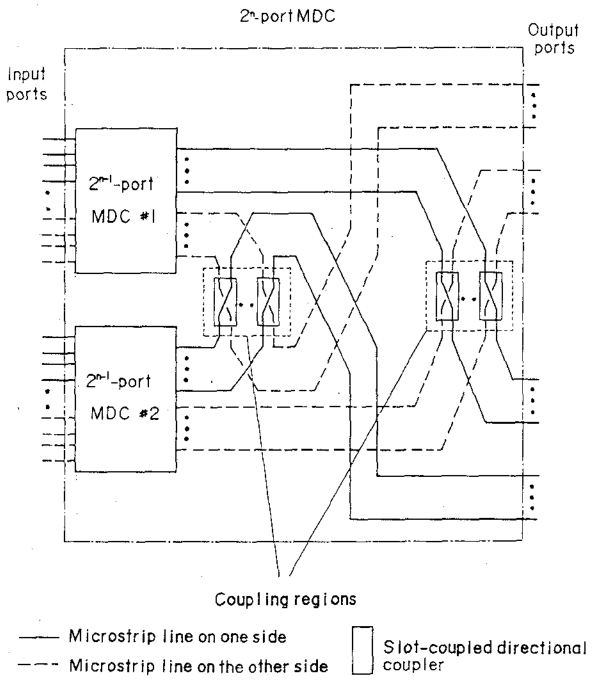


Fig. 11. 2^n-port MDC configuration.

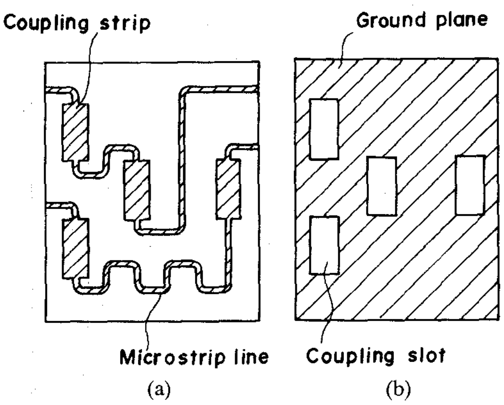


Fig. 12. Circuit pattern of a fabricated 4-port MDC. (a) Pattern of substrate surface. (b) Pattern of ground plane.

B. Performances of MDC's

When MDC's are used for beam-forming networks or multiport amplifiers, the electrical line lengths between input and output ports must be designed to be exactly equal. If an MDC is made by planar construction, electrical line lengths are easily adjusted to the desired value by designing microstrip line lengths between input and output ports.

The circuit patterns of a fabricated 4-port MDC are shown in Fig. 12. The microstrip length between input and output ports on this pattern is designed so that the electrical line lengths are equally set. The pattern is the same on each side, so it is easy to make the electrical line lengths equal in order to obtain good performance.

Fig. 13 shows a photograph of a fabricated 4-port MDC. The coupling strip width (W), coupling slot width (G), and coupling lengths (L) at the coupling region are the same as those of a 3 dB coupler. The dimensions of the

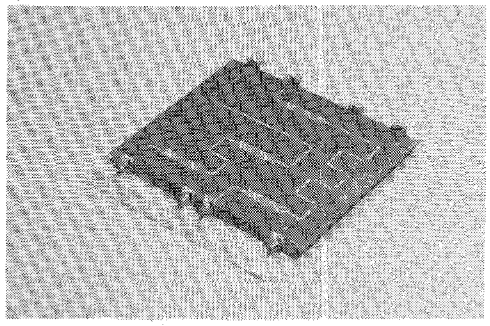


Fig. 13. Photograph of 4-port MDC.

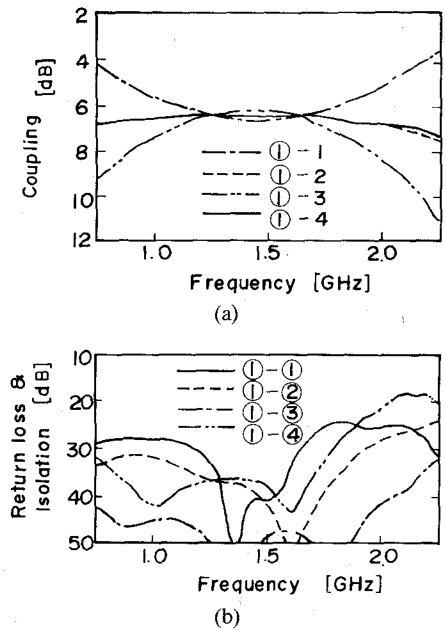


Fig. 14. Frequency characteristics of a planar 4-port slot-coupled MDC. (a) Coupling. (b) Return loss and isolation.

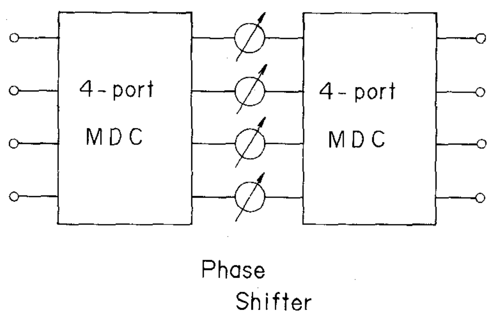


Fig. 15. Construction of a beam-forming network using MDC's.

fabricated 4-port MDC are 150×180 mm^2. The frequency performance of the 4-port MDC is shown in Fig. 14. Couplings of 6.4 ± 0.4 dB with more than 25 dB return loss and more than 30 dB isolation were obtained for the 4-port MDC over the 1.2–1.8 GHz frequency band. The measured coupling results for the 4-port MDC closely matched the calculated results.

Fig. 15 shows an example of a beam-forming network using four-port MDC's. If the electrical line lengths between input and output ports of the 4-port MDC are

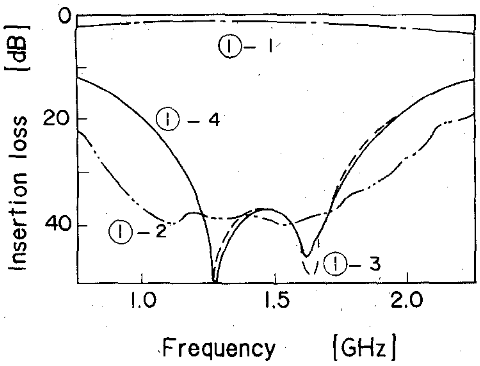


Fig. 16. Frequency performance of two connected 4-port MDC's.

exactly equal, the power from one input port transmits to only one corresponding output port by setting specific phase values of the phase shifters between two MDC's. For example, where the phase value of each phase shifter is 0°, the power from one input port transmits to only one output port.

The measured results of connecting two MDC's are shown in Fig. 16. In this configuration, each phase shifter shown in Fig. 15 is set to 0°. As shown in Fig. 16, input power from input port 1 transmits to only one output port, which shows that the fabricated 4-port MDC's have uniform input–output electrical line lengths.

VI. Conclusion

A design for a slot-coupled directional coupler between two microstrip lines coupling through a rectangular slot in a common ground plane has been proposed and fabricated for the 1.5 GHz band. The experimental results of the slot-coupled directional coupler have been described. The measured results of both tight coupling and loose coupling closely matched the calculated results. A planar multiport directional coupler (MDC) configuration designed by combining slot-coupled directional couplers has also been proposed. The measured results for the 4-port MDC closely matched the calculated results. An effective planar slot-coupled MDC can be easily fabricated and has many useful applications, such as in beam-forming networks and multiport amplifiers.

Acknowledgment

The authors wish to thank Dr. Furuhama of ATR for his continuous encouragement.

References

[1] J. Frey and K. B. Bhasin, *Microwave Integrated Circuits*. Norwood, MA: Artech House, 1985.

[2] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*. Norwood, MA: Artech House, 1979.

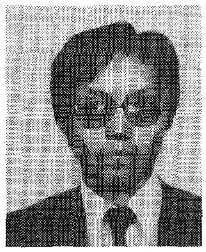
[3] U.S. Patent 3 575 674, 1971.

[4] W. A. Sandrin, "The Butler matrix transponder," *COMSAT Tech. Rev.*, vol. 4, no. 2, pp. 319–345, 1974.

[5] S. Egami and M. Kawai, "Multiport power combining transmitter for multibeam satellite communications," *Trans. IECE Japan*, vol. J69-B, pp. 206–212, Feb. 1986.

[6] J. Reed and G. J. Wheeler, "A method of analysis of symmetrical four-port networks," *IRE Trans. Microwave Theory Tech.*, vol. MTT-4, Oct. 1956.

[7] M. Kawai, "Multiport-coupling beam-switching network for satellite use," *Trans. IECE Japan*, vol. J66-B, pp. 329–336, Mar. 1983.

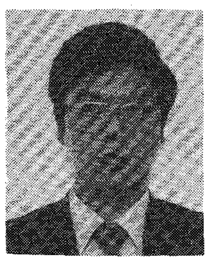


Toshiaki Tanaka (M'87) was born in Osaka, Japan, on May 23, 1951. He received the B.S. and M.S. degrees in communication engineering from Osaka University, Osaka, Japan, in 1975 and 1977, respectively.

In 1977, he joined the NTT ECL System, Yokosuka, Kanagawa-ken, Japan, where he worked on on-board equipment for satellite communications systems.

From 1986 to 1988, he was with the Advanced Telecommunications Research Institute International (ATR), Osaka, Japan, where he has been engaged in research and development of microwave passive components and GaAs monolithic microwave integrated circuits (MMIC's). In 1988 he was appointed Executive Engineer of the NTT Network Systems Development Center, Tokyo, Japan. Since then he has been engaged in the development of integrated networks.

Mr. Tanaka is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.



Kikuo Tsunoda (M'88) was born in Nagoya, Japan, on February 24, 1956. He received the B.E. degree in applied physics engineering from Nagoya University, Nagoya, Japan, in 1979.

In 1979, he joined Murata Manufacturing Company, Ltd., Kyoto, Japan, where he was engaged in research and development work on microwave filters. In 1987, he was temporarily transferred to ATR Optical and Radio Communications Research Laboratories in Osaka, Japan, where he has been engaged in research on microwave passive components.

Mr. Tsunoda is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Masayoshi Aikawa (M'78) was born in Saga, Japan, on October 16, 1946. He received the B.S., M.S., and Dr. Eng. degrees in electronics engineering from Kyushu University, Fukuoka, Japan, in 1969, 1971, and 1985, respectively.

In 1971, he joined the Musashino Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Tokyo, Japan, where he was engaged in research and development on microwave and millimeter-wave integrated circuits, MIC's, and MMIC's and equipment for 20 GHz digital radio trunk transmission systems and 26 GHz subscriber radio systems. In 1986, he joined the ATR Optical and Radio Communications Research Laboratories in Osaka, Japan, where he is currently engaged in research on basic techniques for future mobile communication systems.

Dr. Aikawa is a member of the Institute of Electronics, Information and Communication Engineers of Japan.