Double-Sided MIC's and Their Applications

MASAYOSHI AIKAWA, MEMBER, IEEE, AND HIROYO OGAWA, MEMBER, IEEE

(*Invited Paper*)

Abstract —This paper presents the basic concept and features of double-sided microwave integrated circuits (double-sided MIC's), which effectively utilize various kinds of transmission lines on both sides of a substrate. The fundamental circuits such as 180° hybrids (magic T's) and many application circuits described in this paper are very useful in developing microwave and millimeter-wave band equipment. The concept of double-sided MIC technique can be also applied to MMIC's.

I. Introduction

MICROWAVE integrated circuits (MIC's) are fundamental to microwave technology and are widely used in microwave and millimeter-wave band equipment. Most MIC's use microstrip lines as the main transmission lines. On the other hand, coplanar waveguides, slotlines, finlines, and their modified transmission lines, such as coupled microstrip slotlines, have recently been utilized in MIC's. The authors [1]–[3] and several other researchers [4]–[6] have developed "doubled-sided MIC's," which effectively utilize these transmission lines on both sides of the substrate.

This paper describes the basic concept and features of double-sided MIC's, as well as fundamental components together with application circuits. The fundamental components and application circuits are very important in practical MIC's and are also useful in applications of finline circuits. Double-sided MIC's include a substantial number of planar circuits, which are mainly constructed of coplanar waveguides and slotlines. Accordingly they have great potential for applications to monolithic microwave integrated circuits (MMIC's) because of the planar structure.

This paper first discusses double-sided MIC structure and features and then describes fundamental circuits such as 180° hybrids and several application circuits including a double-balanced modulator.

II. Double-Sided MIC's and Their Features

Double-sided MIC's successfully use several kinds of transmission lines such as microstrip lines, slotlines, coplanar waveguides, and their modified transmission lines on both sides of the substrate. That is why this type of MIC is referred to as a double-sided MIC. Double-sided MIC's have many practical advantages owing to the effects of combining several kinds of transmission lines, and the effective use of both sides of the substrate. The advantages are as follows.

A. Excellent Circuit Functions

1 In addition to a number of transmission line transitions which have been reported [7], [8], series T junctions and parallel T junctions are easily realized, as described in Section III. Series T junctions should be very useful double-sided MIC circuits, which are very difficult to realize in conventional microstrip line MIC's.
2) Circuits of the balanced type such as balanced mixers, balanced frequency doublers, balanced modulators, and push-pull amplifiers are easily constructed through the use of "balance/unbalance transitions," which are described in Section IV.
3) A very tight line coupling ($2 \sim 3$ dB) is also achieved without any difficulty [3], [4], [9]. As a good example of double-sided MIC couplers, a microstrip–slotline directional coupler is described in Section III.

B. Greater Design Flexibility

1) Higher integration can be achieved by using both sides of the substrate effectively.
2) Active or passive devices are easily mounted in series with, or parallel to, transmission lines, because the double-sided MIC's use coplanar type lines such as slotlines or coplanar waveguides.
3) A very wide range of transmission line impedance is available. For instance, a modified transmission line such as the microstrip line with a slot on the ground conductor shown in Fig. 1 can have a very high impedance, about $200 \sim 300$ Ω, if necessary [10]. This kind of transmission line is used effectively in developing a 3 dB directional coupler, as described in Section III.
4) Line crossings can be eliminated even in a comparatively complicated circuit such as a double-balanced mixer [1].

The practical advantages of double-sided MIC's described above are summarized in Fig. 2.

Manuscript received January 25, 1988; revised July 26, 1988.
M. Aikawa is with the ATR Optical and Radio Communications Research Laboratories, Osaka, Japan.
H. Ogawa is with the Network Systems Development Center of NTT, Yokusuka, Japan.
IEEE Log Number 8824978.

0018-9480/89/0200-0406$01.00

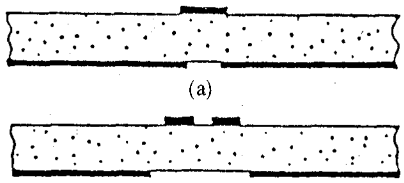


Fig. 1. Modified microstrip lines with high characteristic impedance. (a) Microstrip line with a slit (coupled microstrip–slotline). (b) Coupled microstrip lines with a slit.

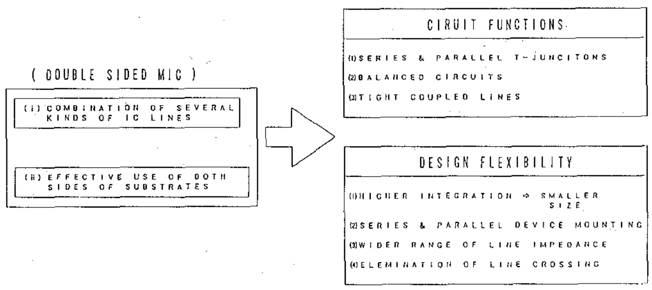


Fig. 2. Features of double-sided MIC's.

TABLE I
T JUNCTIONS IN DOUBLE-SIDED MIC'S

DIVIDING PORTS ②, ③ / ADDING PORT ①	STRIPLINE	SLOTLINE	COPLANAR WAVEGUIDE
STRIPLINE	PARALLEL (a)	PARALLEL (b)	PARALLEL (c)
SLOTLINE	SERIES (d)	SERIES (e)	SERIES (f)
COPLANAR WAVEGUIDE	PARALLEL (g)	PARALLEL (h)	PARALLEL (i)

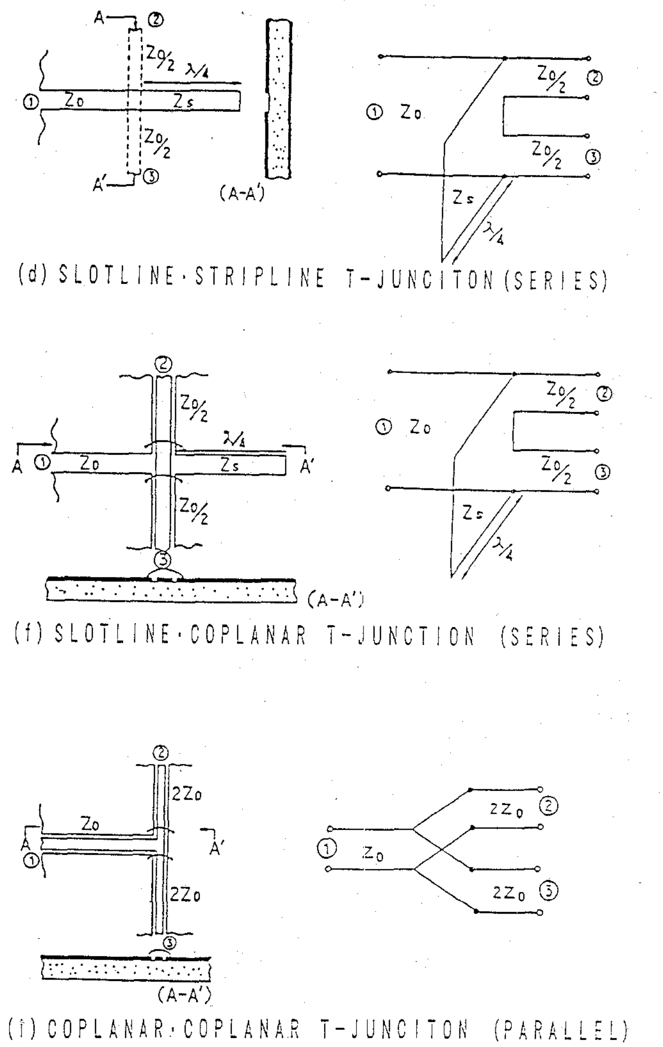


Fig. 3. Circuit configurations of T junctions ((d), (f), and (i) in Table I).

III. Fundamental Circuits of Double-Sided MIC's

By virtue of the many advantages of double-sided MIC's, many fundamental circuits are available. These play important roles in practical double-sided MIC's. Examples of fundamental circuits include transmission line transitions, T junctions, balun circuits, power dividers, directional couplers, and 180° hybrids (called magic T's in this paper). Some of these have been reported [2]–[4], [7], [8] by other researchers and the authors. In this section, T junctions, 180° hybrids, and directional couplers are described as good examples of fundamental circuits.

A. T Junctions

T junctions are very important as fundamental circuits and as transmission line transitions in double-sided MIC's. Table I summarizes the main T junctions. The most important fact is that series T junctions (indicated as (d), (e), and (f) in Table I) are available without difficulty due to the balance mode of slotlines. Series T junctions are not readily available in conventional microstrip line MIC's. Fig. 3 shows three circuit configurations of T junctions ((d), (f) and (i) in Table I) and their equivalent circuits. The other T junctions are relatively widely known and are easily realized. T junctions are effectively used to compose magic T's, as described in the following subsection.

B. Magic T's (180° Hybrid Circuits)

Magic T's are one of the best examples of double-sided MIC components. The authors previously proposed magic T's [2] which effectively utilized coupled slotlines. This paper shows other types of magic T's—those composed of series T junctions and parallel T junctions described in the previous subsection. It is commonly known that a metallic

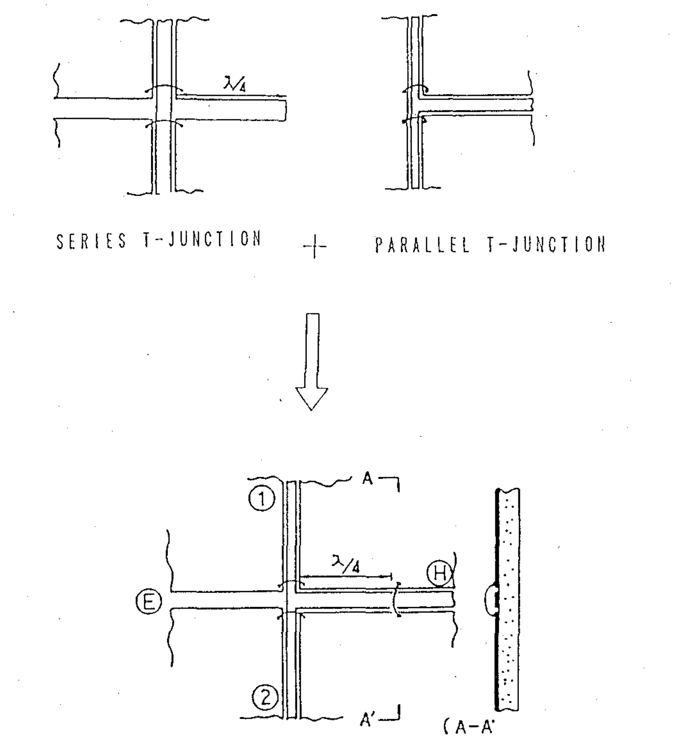


Fig. 4. Basic design concept of a magic T (type (a)).

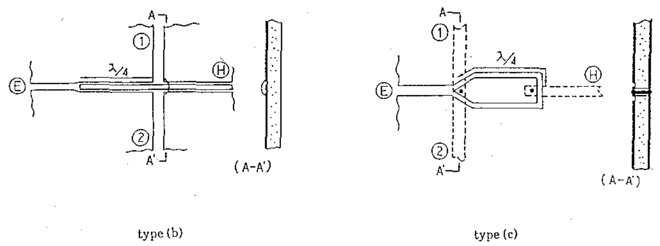


Fig. 5. Circuit configurations of magic T's of type (b) and type (c).

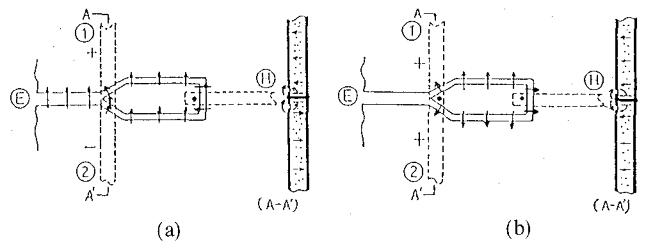


Fig. 6. Schematic behavior of type (c) magic T (see Fig. 5). (a) Out-of-phase. (b) In-phase.

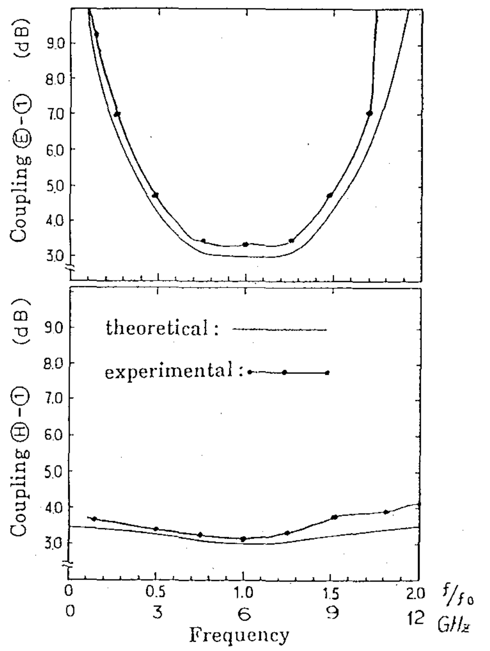


Fig. 7. Out-of-phase (Ⓔ–①) coupling and in-phase (Ⓗ–①) coupling performance of a magic T (type (c) in Fig. 5).

waveguide magic T is composed of an E-plane T junction (which corresponds to a series T junction) and an H-plane T junction (which corresponds to a parallel T junction). In the same way, many MIC magic T's are readily available by combining the series T junctions and parallel T junctions summarized in Table I. Fig. 4 shows an example of the circuit-composing method, where a new magic T (called type (a) in this paper) is composed of a slot/coplanar series T junction (Fig. 3(f)) and a coplanar/coplanar parallel T junction (Fig. 3(i)). Ports Ⓔ and Ⓗ correspond to, respectively, the E arm and H arm of a metallic waveguide magic T, and ports ① and ② are the remaining two ports. Many magic T's are available using the same composing method. Fig. 5 shows circuit configurations of the other typical magic T's.

The fundamental behavior of these magic T's can be understood by examining type (c) in Fig. 5. The behavior of the other magic T's is the same in principle. Fig. 6 shows a schematic explanation of the magic T (type (c)), where arrows indicate the electric field in the slotlines. Magic T performance is analyzed in terms of two orthogonal modes (out-of-phase and in-phase excitations), because the circuit is symmetrical with respect to the Ⓔ–Ⓗ axis. The out-of-phase mode is excited by out-of-phase signals of the same amplitude at ports ① and ② or, conversely, by a signal from port Ⓔ. The in-phase mode is excited by in-phase signals of the same amplitude at ports ① and ② or, conversely, by a signal from port Ⓗ. In principle, the in-phase power dividing/coupling has a broad frequency bandwidth, because the frequency band is limited only by the effect of the impedance transformer. Out-of-phase power dividing/coupling, on the other hand, has a comparatively narrow frequency bandwidth due to the effect of the quarter-wavelength slotlines.

Fig. 7 shows the theoretical performance of a magic T (type (c) in Fig. 5) and also the experimental results for a center frequency of 6 GHz. The magic T is fabricated on a 0.635 mm alumina (Al_2O_3) substrate with a relative dielectric constant of 9.6. The experimental results coincide well with the theoretical performance, as shown in Fig. 7. These magic T's can be realized even in a very high frequency band such as the millimeter-wave band.

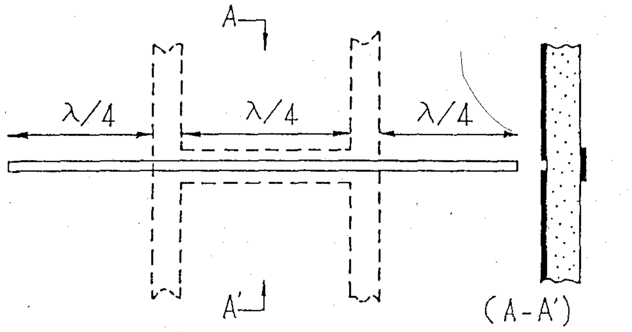
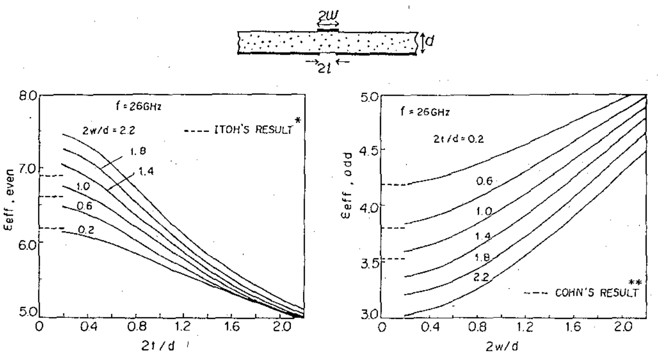
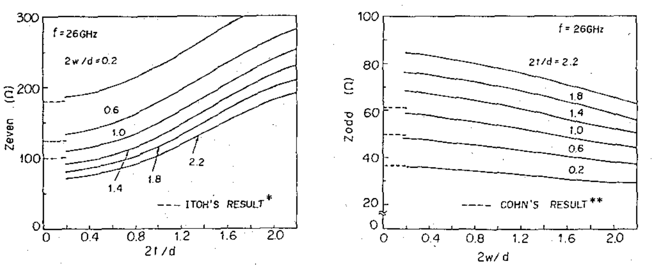


Fig. 8. Circuit configuration of coupled microstrip-slotline directional coupler.



(a) (b)

Fig. 9. Effective dielectric constant of coupled microstrip–slotline (ϵ_r = 9.6). (a) Even mode. (b) Odd mode. *T. Ito and R. Mittra, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, p. 496, July 1983. **S. B. Cohn, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, p. 768, Oct. 1969.

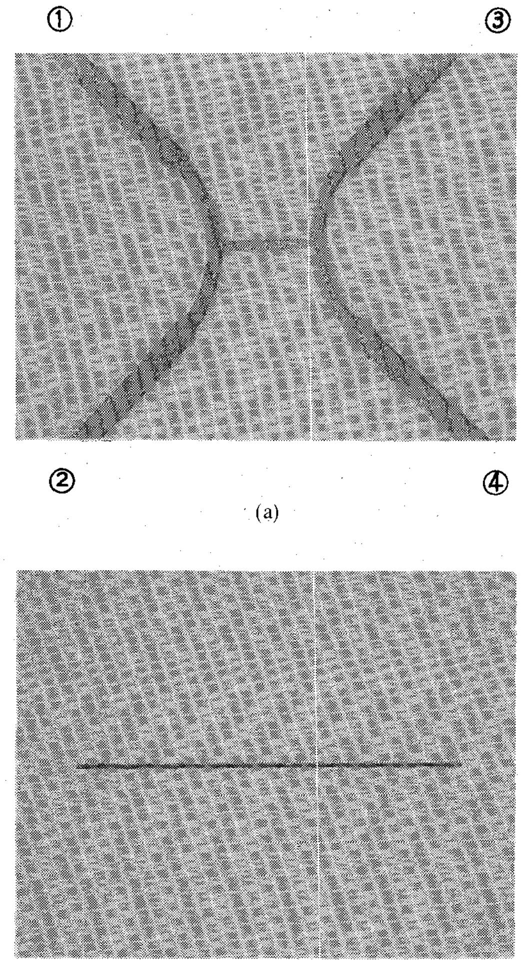


(a) (b)

Fig. 10. Characteristic impedance of coupled microstrip–slotline (ϵ_r = 9.6). (a) Even mode. (b) Odd mode. For an explanation of asterisks, see Fig. 9.

C. Coupled Microstrip–Slotline Directional Coupler

The double-sided MIC directional coupler was first proposed by de Ronde [4]. Fig. 8 shows the circuit configuration of the coupled microstrip–slotline directional coupler. This type of hybrid coupler can be analyzed by Shiek's method [11]. The main feature of the coupler is that a tight coupling factor can be achieved by practical structural parameters. The dispersion characteristics of the coupled microstrip–slotline were analyzed by the spectral-domain method and the characteristic impedance of two orthogonal modes was calculated [9]. Figs. 9 and 10 show the effective dielectric constant and the characteristic impedance of a coupled microstrip–slotline, respectively. The directional coupler was designed for a center frequency of 26 GHz and was fabricated on a 0.3-mm-thick alumina substrate. The circuit pattern is shown in Fig. 11. Fig. 12 shows the experimental results for the directional coupler. The insertion loss variation is less than 0.5 dB over a range of 25–28.5 GHz. The isolation is greater than 18 dB over a bandwidth of 6 GHz.



(a)

(b)

Fig. 11. Circuit pattern of coupled microstrip–slotline directional coupler. (a) Microstrip line pattern. (b) Slotline pattern.

IV. Application Circuits of Double-sided MIC's

A. Balance/Unbalance Transition Circuit (Balun)

Double-sided MIC's have many advantages, as mentioned above. An important double-sided MIC circuit is the balance/unbalance transition circuit (balun). The circuit configuration is very simple, as shown in Fig. 13. The balance/unbalance transition circuit has the following fea-

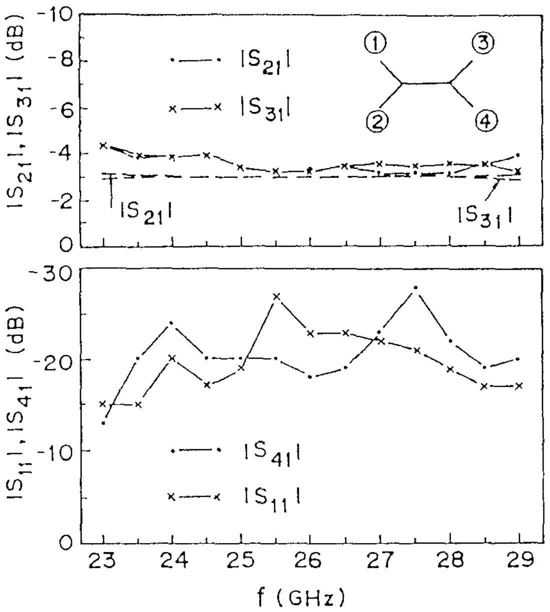


Fig. 12. Frequency performance of a coupled microstrip–slot directional coupler.

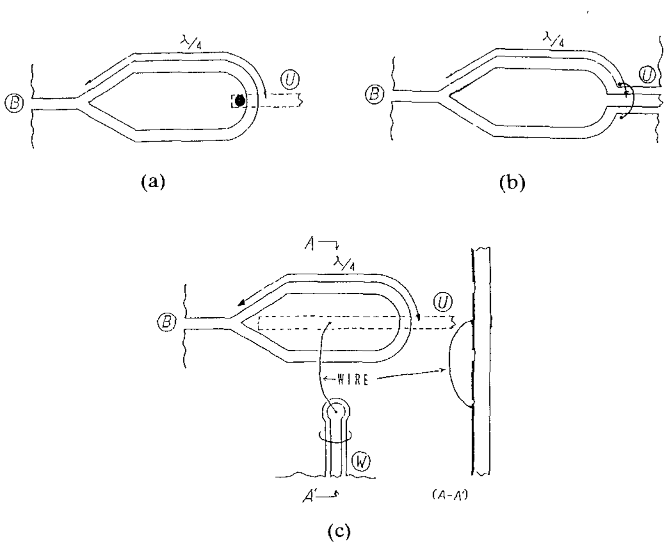


Fig. 13. Circuit configurations of balance/unbalance transition circuits (balun). (a) Slot/microstrip balun. (b) Slot/microstrip balun. (c) Slot/microstrip balun with a wire port.

tures:

1) Remarkable isolation between the balance line (slotline) and the unbalance line (microstrip line) is obtained over a wide frequency range due to the symmetric configuration.
2) Beam-lead devices are easily connected on transmission lines because the circuit consists of slotlines.
3) A dc return path for devices is not required because slotlines are used.
4) Balanced microwave circuits such as modulators, mixers, and doublers are obtained by the combination of balance/unbalance transition circuits and switching/nonlinear devices.

The circuit shown in Fig. 13(a) consists of a series slot T junction, two quarter-wavelength slotlines, a through-hole conductor, a slotline (balance line), and a microstrip line (unbalance line). The through-hole conductor connects the microstrip line and the inside conductor surrounded by two quarter-wavelength slotlines. The intermediate frequency (IF) signal is obtained from, or the modulating pulse signal is supplied to, the inside conductor through the through-hole conductor. Despite the precise machining process for the through-hole conductor, a discontinuity exists between the microstrip line and the slotline. The higher frequency of the transition characteristics is limited by the stray elements caused by the discontinuity [12]. Thus the transition circuit shown in Fig. 13(a) can be operated in a lower microwave frequency band. The other balance/unbalance transition circuit, which uses a coplanar waveguide instead of a microstrip line, is shown in Fig. 13(b). In principle, the performance is the same as the circuit shown in Fig. 13(a).

A circuit which uses an open-circuited quarter-wavelength microstrip line instead of a through-hole conductor is shown in Fig. 13(c). The upper frequency attained is improved by eliminating the discontinuity of the through-hole conductor. A wire to supply the modulating pulse or obtain the IF signal is bonded on the inside conductor. Although the RF signal propagates on slotlines, the port of the wire is isolated from the RF circuit, because of concentration of the RF electromagnetic field in the slotline, and the high series inductance of the wire. The microstrip line does not contact the inside conductor, and an open-circuited quarter-wavelength microstrip line acts as a bandpass filter. This means that low-frequency signals such as the IF signal and modulating pulses do not couple with the output microstrip line. The ports shown in Fig. 13(c) are isolated from each other without filters.

The equivalent circuits of the baluns in Fig. 13 are shown in Fig. 14. The series slot T junction and the transition circuit of the slotline/microstrip line are expressed by ideal transformers. The balance/unbalance transition circuit described in this paper corresponds to a series–parallel connected circuit. Therefore, from the viewpoint of the equivalent circuit, the balance/unbalance transition circuit can produce any type of balanced microwave circuit, such as a modulator, a mixer, or a frequency doubler.

B. Balanced Microwave Circuit

Fig. 15 shows some examples of balanced microwave circuits which use the balance/unbalance transition circuit [12]–[19]. In Fig. 15, balanced circuits (a) and (b) can be used as PSK modulators, phase detectors, and mixers. If balanced circuit (a) in Fig. 15 is used as a PSK modulator, the modulating pulse is supplied to the diodes through the microstrip line. The carrier propagates along each slotline according to the polarity of the modulating pulse. If the balanced circuits of (b) in Fig. 15 are used as mixers, an IF signal is obtained from the wire port. The isolation between the RF and LO ports depends on the uniformity of

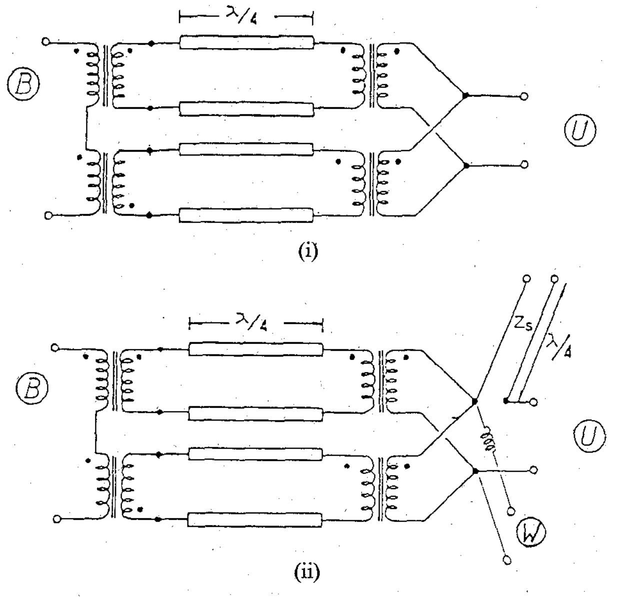


Fig. 14. Equivalent circuits of double-sided balance/unbalance transition circuits. (i) Equivalent circuit for (a) and (b) in Fig. 13. (ii) Equivalent circuit for (c) in Fig. 13.

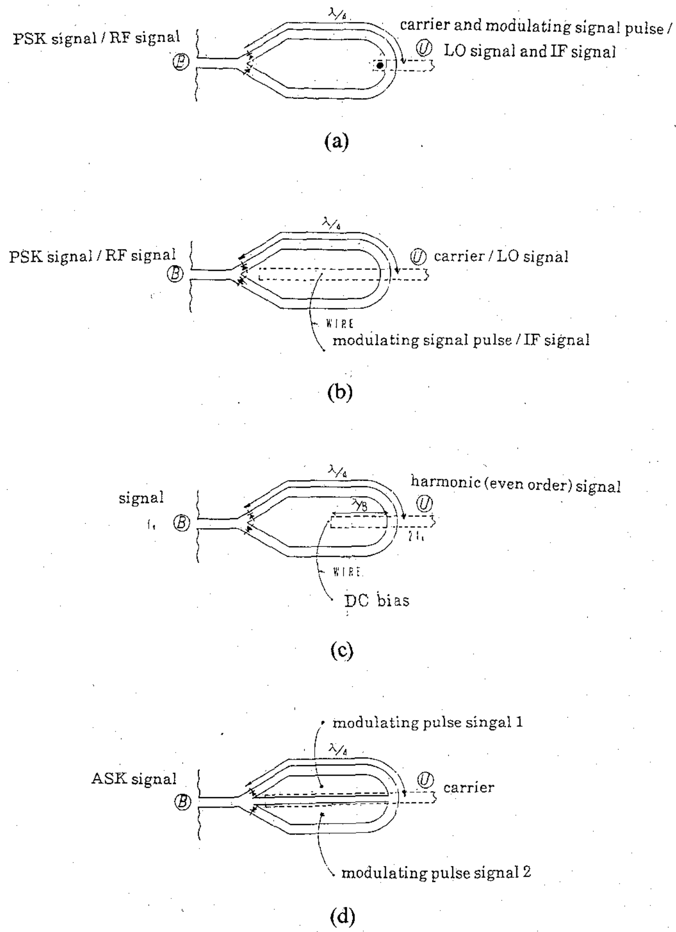


Fig. 15. Double-sided balanced microwave circuits. (a) Balanced PSK modulator/phased detector/mixer. (b) Balanced PSK modulator/phased detector/mixer with a wire port. (c) Balanced frequency doubler. (d) Amplitude shift keying (ASK) modulator.

the two mixing diodes. The direction of the diodes connected on slotlines in Fig. 15(b) is the same as that shown in Fig. 15(a).

The frequency doubler shown in Fig. 15(c) has its diodes bonded to the slotlines differently. The wire provides a dc bias voltage to the diodes. The length of an open-circuited microstrip line is one eighth of the carrier wavelength. The input signal of frequency f_0 at port Ⓑ is supplied out of phase to the two diodes. The second-harmonic signal of the frequency, $2f_0$, and the higher even harmonics are generated in phase by the diodes. The desired second-harmonic signal is then obtained from output port Ⓤ through the $\lambda/8$ microstrip line, which plays the role of a bandpass filter for the second-harmonic signal. Odd harmonics as well as the input signal propagate out of phase along the $\lambda/4$ slotlines and are short-circuited at the junction of the slotlines and the microstrip line. Thus, all odd harmonics are decoupled from output port Ⓤ. In this way, the odd harmonics and the fundamental frequency can be suppressed without filters.

In Fig. 15(d), the inside conductor is divided into two parts. The dc bias voltage can be supplied independently to the diodes. The constant-resistance ASK modulator can be realized by a divided structure [19].

Thus, many functional microwave circuits of small circuit configuration can be obtained by using the double-sided MIC technique. In principle other devices, for example MESFET's, can be employed in these circuits instead of diodes.

C. Experimental Results of Double-Balanced BPSK Modulator

Fig. 16 shows the circuit configuration of the double-balanced BPSK (binary PSK) modulator. Two balance/unbalance transition circuits and four switching diodes are required to construct the double-balanced circuits. The transition circuit which combines the modulating pulse signal and the carrier is realized by the magic T. These two signals are decoupled from the PSK signal of the output port because of the balance/unbalance transition circuit composed of the combination of slotlines and microstrip lines. Four beam-lead diodes are mounted on the slotline T junction circuits as shown in Fig. 16.

Fig. 17 shows the fundamental behavior of the BPSK modulator. Arrows represent the schematic electric field expression of the carrier, which propagates along the slotlines. The modulating pulses fed to port Ⓟ are divided in phase through the magic T into two slotlines. The pulse is then supplied to the switching diodes. However, the RF carrier fed to port Ⓒ is divided 180° out of phase through the magic T into two slotlines, and added again at port Ⓜ. The phase of the RF carrier derived at port Ⓜ is shifted 180° according to the polarity of the modulating pulse. Fig. 17 shows the two cases where positive and negative pulses are supplied to four diodes, respectively. Thus, a BPSK modulated carrier is obtained from port Ⓜ.

The modulator was designed for a carrier frequency of 6 GHz. Schottky barrier beam-lead diodes are employed as

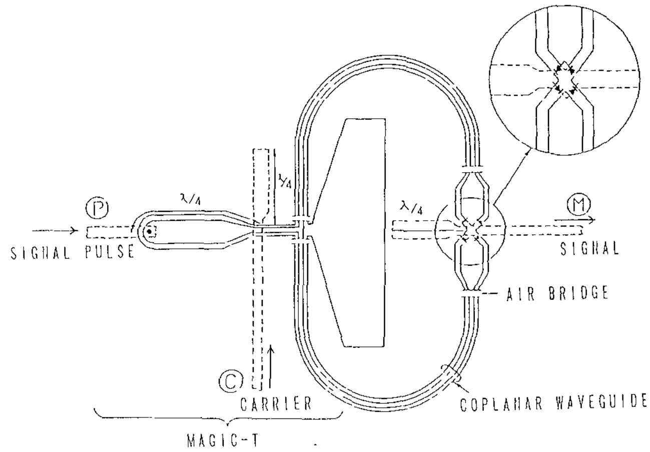


Fig. 16. Circuit configuration of double-balanced BPSK modulator.

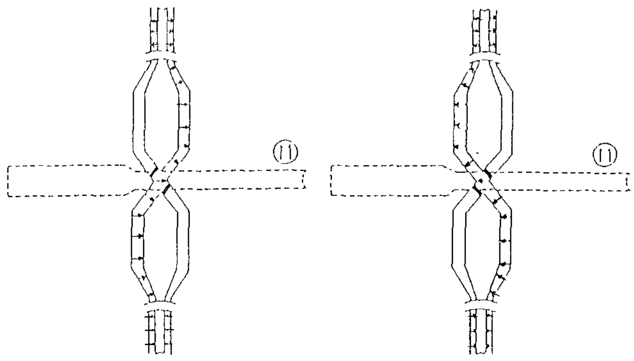


Fig. 17. Principle of BPSK modulator. (a) Positive pulse. (b) Negative pulse.

switching elements, because they are suitable for gigabit-rate switching in the high-frequency band by virtue of their majority carrier operation. The measured modulation loss at 6 GHz was 2.6 dB. The diode used here has an ON-state impedance of $6+j14\ \Omega$ and an OFF-state impedance of $17-j205\ \Omega$ at 6 GHz. The theoretical modulation loss is 0.9 dB. The remaining loss of 1.7 dB was attributed to the insertion loss of the magic T of 0.8 dB and the conduction loss of the transmission lines. The isolation between any two ports is greater than 30 dB over a one-octave bandwidth. The measured modulating phase error is less than $\pm 1°$, which means that the conventional photolithographic technique used here is sufficiently accurate to align the circuit patterns on either side of the substrate in several GHz bands. If the two-side mask aligner is used for circuit pattern alignment, there is no problem with the alignment accuracy, even in the millimeter-wave band. The double-sided MIC double-balanced BPSK modulator can operate at a high-bit-rate data stream of about 2 Gb/s. This circuit can also be used as a double-balanced mixer or a phase detector with a very wide bandwidth.

V. Conclusion

A double-sided MIC concept and its features have been discussed and several fundamental circuits and application circuits are described. They utilize both substrate surfaces and employ microstrip lines, slotlines, coplanar waveguides, and their modified transmission lines. Due to the effective use of both substrate surfaces, many functional microwave circuits which are difficult to realize by conventional means are obtained for microwave bands. Despite the complicated structure of double-sided MIC's, they can easily be fabricated with standard MIC techniques. The double-sided MIC's described in this paper are summarized as follows:

1) T junction circuits between MIC transmission lines;
2) fundamental circuits such as magic T's, and directional couplers with tight coupling;
3) application circuits such as a balanced mixer, balanced frequency doubler, and double-balanced modulator.

The double-sided MIC's are expected to have wide applications in microwave and millimeter-wave bands. These circuits are useful in constructing microwave or millimeter-wave transmitter/receiver modules [20]. The double-sided MIC technique concept can also be applied to MMIC's [21]. Many functional MMIC components based upon the double-sided MIC idea will be created in the near future.

References

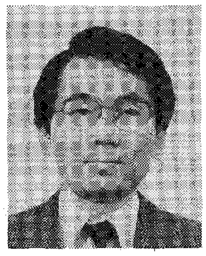
[1] M Aikawa and H. Ogawa, "C Band MIC double-balanced modulator for 2Gbit/s PSK," in *Proc. 1979 ISCAS*, July 1979, pp 818–821.
[2] M. Aikawa and H. Ogawa, "A new MIC magic-T using coupled slot lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp 523–528, June 1980.
[3] M. Aikawa, "Microstrip line directional coupler with tight coupling and high directivity," *Trans. IECE*, vol. 60-B, 4, pp 253–259, Apr. 1977.
[4] F. C. de Ronde, "A new class of microstrip directional couplers," in *IEEE MTT-S Int. Microwave Symp. Dig.*, May 1970, pp 184–186.
[5] M. Houdart, "Coupled line directional coupler for M I.C," in *Proc. 8th European Microwave Conf.*, 1978, pp. 79–83.
[6] E. A Mariani and J. P. Agrios, "Slot-line filters and couplers," *IEEE Trans. Microwave Theory Tech.*, vol., MTT-18, pp. 1089–1095, Dec. 1970.
[7] M. Houdart and C. Aury, "Various excitations of coplanar waveguide," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1979, pp. 116–118.
[8] J. B. Knorr, "Slot-line transitions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp 548–554, May 1974.
[9] H. Ogawa, T. Hirota, and M. Aikawa, "Coupled microstrip-slot-line directional coupler," *Trans. IECE*, vol. 65-B, pp. 882–889, July 1982.
[10] M. Aikawa, "Wide-band strip-line reverse-phase hybrid ring in GHz band," *Trans. IECE*, vol. 58-B, pp. 521–528, Oct. 1975.
[11] B. Shiek, "Hybrid branchline couplers—A useful new class of directional couplers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 864–869, Oct. 1974.
[12] M Aikawa and H. Ogawa, "A 2Gb/s double-balanced PSK modulator using coplanar waveguides," in *1979 ISSCC Dig. Tech. Pap.*, Feb. 1979, pp. 172–173.
[13] J. K. Houton and J. S. Takeuchi, "Recent development in microwave slotline mixers and frequency multipliers," in *IEEE MTT-S Int. Microwave Symp. Dig.*, May 1970, pp. 196–199.
[14] L. E. Dickens and D. W. Maki, "An integrated-circuit balanced mixer, image and sum enhanced," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 276–281, Mar 1975.
[15] L. E. Dickens and D. W. Maki, "A new phase-type image enhanced mixer," *IEEE MITT-S Int Microwave Symp. Dig.*, May 1975, pp. 149–151.

[16] H. Ogawa, M. Aikawa, and K. Morita, "*K*-band integrated double-balanced mixer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 180–185, Mar. 1980.
[17] H. Ogawa, M. Akaike, M. Aikawa, T. Karaki, and J. Watanabe, "A 26-GHz band integrated circuit of a double-balanced mixer and circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 34–41, Jan. 1982.
[18] H. Ogawa, M. Aikawa, and M. Akaike, "Integrated balanced BPSK and QPSK modulators for the *Ku*-band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 227–234, Mar. 1982.
[19] Y. Tarusawa, H. Ogawa, and T. Hirota "A new constant-resistance ASK modulator using double-sided MIC," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 819–822, Sept. 1987.
[20] H. Ogawa, K. Yamamoto, and N. Imai, "A 26-GHz high-performance MIC transmitter/receiver for digital radio subscriber systems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1551–1556, Dec. 1984.
[21] T. Hirota, Y. Tarusawa, and H. Ogawa, "Uniplanar MMIC hybrids —A proposed new MMIC structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 576–581, June 1987.

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 did research and development work on microwave and millimeter-wave integrated circuits, MIC's, MMIC's and equipment for 20 GHz digital radio trunk transmission systems and 26 GHz subscriber radio systems. In 1986, he joined ATR Optical and Radio Communications Research Laboratories, 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.



Hiroyo Ogawa (M'84) was born in Sapporo, Japan, in 1951. He received the B.S., M.S., and Dr. Eng. degrees in electrical engineering from Hokkaido University, Sapporo, in 1974, 1976, and 1983, respectively.

He joined the Yokosuka Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Yokosuka, in 1976. He has been engaged in research on microwave and millimeter-wave integrated circuits and monolithic integrated circuits and the development of subscriber radio systems. From June 1985 to June 1986, he was a Postdoctoral Research Associate at the University of Texas at Austin, on leave from NTT. Since 1987, he has been designing the subscriber radio equipment at the Network Systems Development Center of NTT.

Dr. Ogawa serves on the MTT-S Symposium Technical Program Committee and is a member of an MTT Technical Committee (MTT-6). He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.