sary. This, together with typical high dielectric constants for insulators leads to capacitance values which, indeed, cannot be matched to the common form of microstrip line. In addition, inductance of the metallic finger is too high to permit matching.

The importance of developing a technology for fabricating diodes has been pointed out in this paper. It is, indeed, an overriding consideration in the design of diodes. Series resistance, for example, can be augmented to a very marked degree by the presumed "low resistance" ohmic contacts to each region. The problems in the application of gallium arsenide are primarily those of establishing good junctions of small area and low leakage, and of making good contacts to the bulk regions. Other examples of technological problems are the preparation of small area junctions and of contacts to these areas, the development of suitable etching techniques to prevent the formation of surface channels with high capacitances, the control of diffusion to prevent serious degradation of r_s during the creation of a nonuniform doping distribution, and the development of etching and handling techniques for thinner wafers. These problems will yield to exploration, of course, but they still constitute the greatest barrier in the transition from a practical semiconductor diode to an ideal variable capacitance.

Fast Microwave Logic Circuits*

D. J. BLATTNER† AND F. STERZER†

Summary—**In a carrier-type digital computer system, binary information can be represented by the presence or absence of an RF pulse in a given time interval. Using strip-line printed circuit techniques and point-contact diodes, passive AND and NOT gates were constructed which operate with RF pulses of less than 2 mμsec duration (*i.e.*, an effective pulse repetition rate of 500 mc), at a carrier frequency of 3000 mc. The basic gates were combined to form half-adders. Unlike other carrier approaches, these circuits keep the information in RF form through all steps of the logic operations; *i.e.*, both inputs and outputs of all elements are RF pulses.**

INTRODUCTION

In a digital computer operating at an effective pulse repetition rate of several hundred mc, each binary digit is allotted a time interval of only a few millimicroseconds. A baseband system capable of handling such pulses must have a bandwidth extending well into the UHF or even microwave region.[1] An alternative to the baseband system is a carrier system where the required pass band is centered about a suitable carrier frequency.

For operation at a pulse repetition rate of several hundred mc, a carrier system offers significant advantages over baseband systems. It is very difficult to design active and passive components which operate, starting from dc, with the necessary wide bandwidth.[2]

In a carrier system, on the other hand, the design of components is greatly simplified by the fact that, at a high carrier frequency, components with a comparatively small percentage bandwidth have a large absolute bandwidth. Furthermore, carrier-type devices such as traveling-wave amplifiers, parametric amplifiers and oscillators, hybrid rings, ferrite isolators, etc., can be used advantageously in high-speed carrier systems,[3–7] but are not applicable to baseband systems.

Information can be represented in binary form by the presence or absence of dc pulses in "time slots." In such a system, as shown in Fig. 1(a), binary ones are represented by the presence of dc pulses and binary zeros are represented by the absence of such pulses (dc pulse script). Similarly, the presence or absence of RF pulses (RF pulse script) can be used to represent binary infor-

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† Electron Tube Div., Radio Corp. of America, Princeton, N. J.

1 In a baseband system, the signals occupy a frequency band starting at or near zero and extending to an upper limit.

2 Logic circuits so far reported, using baseband pulses, are limited to pulse repetition rates of about 50 mc (see Walker, *et al.*, and Horton and Anderson). This speed limitation is primarily caused by the limited gain-bandwidth product of the devices used for amplify- the pulses.

R. M. Walker, D. E. Rosenheim, R. A. Lewis, and A. G. Anderson, "An experimental 50-metacycle arithmetic unit," *IBM J. Res. & Dev.*, vol. 1, pp. 257–278; July, 1957.

J. W. Horton and A. G. Anderson, "A full binary adder employing two negative resistance diodes," *IBM J. Res. & Dev.*, vol. 2, pp. 223–231; July, 1958.

3 W. D. Lewis, "Microwave Logic," presented at the Internatl. Switching Symp., Harvard Univ., Cambridge, Mass.; April, 1957.

4 W. C. G. Ortel, "Nanosecond Logic by Amplitude Modulation at X-Band," and W. R. Beam, D. J. Blattner, and F. Sterzer, "Microwave Carrier Technique for High-Speed Digital Computing," both presented at the Symp. on Microwave Techniques for Computing Systems, Dept. of Interior, Washington, D. C.; March 12, 1959.

5 J. von Neumann, "Non-linear capacitance or inductance switching, amplifying, and memory organs," U. S. Patent No. 2,815,488; December, 1957.

6 E. Goto, "On the application of parametrically excited nonlinear resonators," *J. Elec. Commun. Engrs.* (*Japan*), vol. 38, p. 77; October, 1955. Also, "The parametron, a digital computing element which utilizes parametric oscillation," PROC. IRE, vol. 47, pp. 1304–1316; August, 1959.

7 F. Sterzer, "Microwave parametric subharmonic oscillator for digital computing," PROC. IRE, vol. 47, pp. 1317–1324; August, 1959.

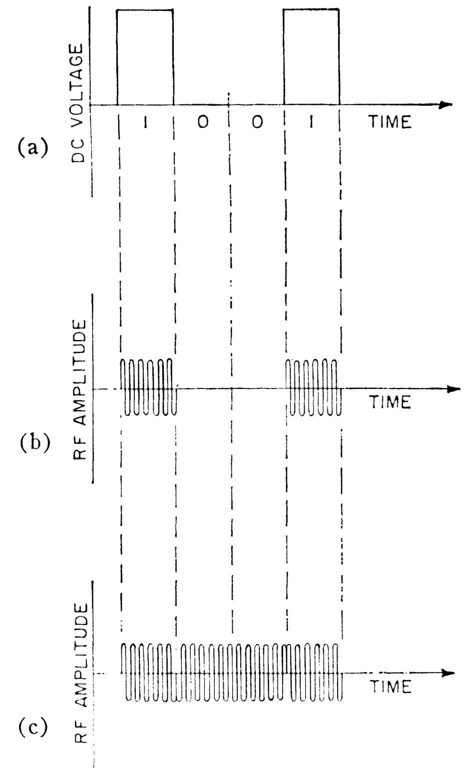


Fig. 1—Three types of script to represent binary information. (a) DC pulse script, (b) RF pulse script, (c) RF phase script.

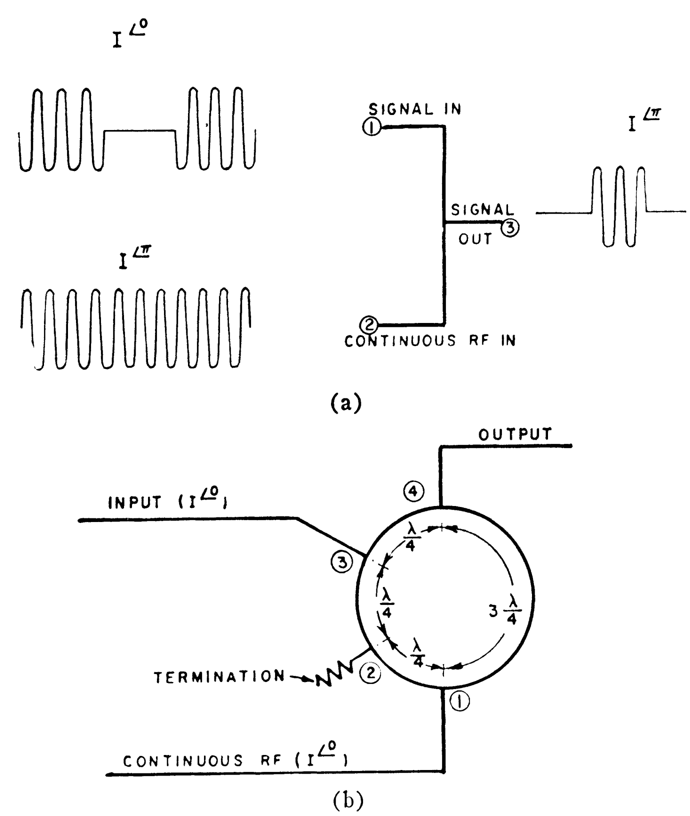


Fig. 2—NOT circuits. (a) A NOT circuit using a simple tee, (b) a NOT circuit using a hybrid ring.

mation, as shown in Fig. 1(b). In another way of coding binary information, shown in Fig. 1(c), a binary one is represented by an RF pulse having a particular phase, and a binary zero is represented by an RF pulse having the same frequency and amplitude but opposite phase (RF phase script). It is possible to convert information from any one of these scripts to any other by means of simple circuits.[4,8] In a complete system it might be convenient to have input and output in dc pulse code, while logic and memory functions are performed in either one or both of the RF codes.

Information coded in phase script can be stored and amplified by use of parametric subharmoninc oscillators.[5–7] Because the several scripts are convertible, subharmonic oscillators can also be used to amplify and store RF information coded in RF pulse script.

This paper describes basic passive logic elements and half-adders using RF pulse coding. All the circuits described were built with strip transmission line;[9] this medium provides compact, low-loss, dispersionless transmission over a wide range of RF frequencies.

Basic Logic Circuits

In principle, any combinatorial logic circuit can be built by using a combination of NOT or complementing circuits and AND circuits.[10] The performance of various designs for these basic logic circuits, using RF pulse coding, is discussed below.

NOT Circuits

Fig. 2(a) shows perhaps the simplest NOT circuit for RF pulse script. The input signal (having amplitude I and phase 0 radians) is fed into arm No. 1 of a simple microwave tee. A continuous signal having the same amplitude, but opposite in phase, is fed into arm No. 2. If there is no input RF pulse fed into arm No. 1 during a given time interval (*i.e.*, a binary zero), there will be an output (representing a binary one) from arm No. 3 caused by the continuous RF input. If, however, there is an input RF pulse applied to arm No. 1, destructive interference between the RF pulse and the continuous RF signal causes complete reflection, and there is no RF output.

One disadvantage of this simple arrangement is that RF power is reflected into the input arm. Although an isolator could be used to absorb the reflected power, it is simpler to use the hybrid-ring circuit shown in Fig. 2(b). The hybrid ring has a circumference equal to one and one-half RF wavelengths and four input arms spaced one-quarter wavelength apart. The input signal is fed into arm No. 3 and continuous RF of the same amplitude, phase, and frequency as the input is fed into arm No. 1. If there is no input, half of the continuous RF is absorbed in the termination of arm No. 2; the other half appears as output at arm No. 4. (Because of destructive interference, no signal leaves the ring at arm No. 3.) If there is an RF input at arm No. 3, the input signal and the continuous RF signal arrive out of

[8] F. Sterzer, "Pulse amplifier with submillimicrosecond rise time," *Rev. Sci. Instr.*, vol. 29, pp. 1133–1135; December, 1958.
[9] M. Arditi, "Characteristics and applications of microstrip for microwave wiring," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 31–56; March, 1955.
[10] R. K. Richards, "Arithmetic Operations in Digital Computers," D. Van Nostrand Co., Inc., New York, N. Y.; 1955.

(a)
(b)
(c)

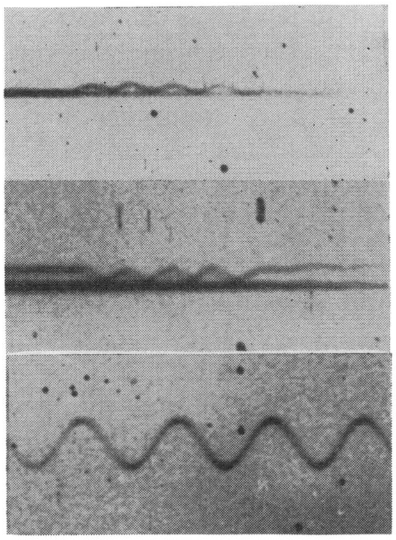


Fig. 3—Oscilloscope tracings illustrating the pulse performance of the NOT circuit. (a) Input pulse train, (b) output pulse train, (c) 200 mc timing signal.

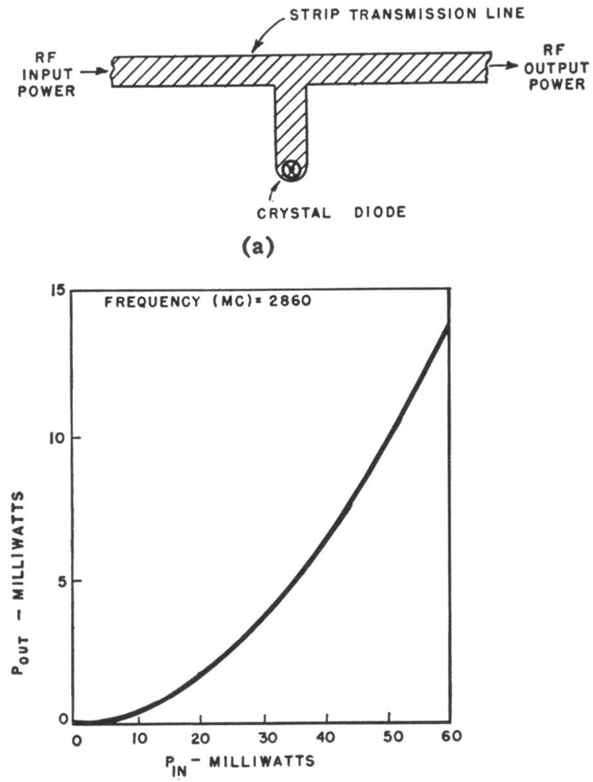
phase at arm No. 4. Consequently, there is no RF output; all of the RF energy is absorbed in the termination in this case.

A stripline version of the circuit shown in Fig. 2(b) was tested with CW RF input, and also with RF pulses having a duration of less than two mμsec. (The RF pulses were produced by a method previously described.[8]) In the CW tests, the RF output signal was reduced by 23 db when an input signal was applied. The results of pulse tests are illustrated by the oscilloscope tracings in Fig. 3. Fig. 3(a) shows the rectified RF input pulses representing the binary digits 1111, together with a base line representing zero RF input. Fig. 3(b) shows the rectified output pulses from the NOT gate; the base line is again visible. Fig. 3(c) shows a 200 mc sine wave used for timing. These three pictures are high-speed photographs of single traces on a traveling-wave oscilloscope.

AND Circuits

An AND gate requires a nonlinear element. Microwave point-contact diodes are suitable nonlinear elements for use with RF pulses.

Fig. 4(a) shows a nonlinear transmission element, called an *expander*, which can be used in an AND circuit. In the expander, a crystal diode, together with a length of stripline, forms an effective quarter-wave stub shunting a transmission line. The diode is biased in the nonconducting direction by means of a battery. If the RF voltage at the diode is insufficient to cause conduction, the diode presents an open circuit to the RF signal. Because this open circuit is a quarter wavelength from the transmission line, an effective short circuit exists across the line, and almost no RF is transmitted. If, however, the RF voltage at the diode is large enough to cause conduction, the RF impedance at the end of the stub is lowered. Therefore, the effective impedance shunting the line is increased, and the RF power appearing at the output is increased. Fig. 4(b) shows the



(b)

Fig. 4—(a) A stripline expander circuit. (b) RF power output vs RF power input for the expander circuit, using a 1N23D crystal diode with 1.5 volts back bias.

(a)

(b)

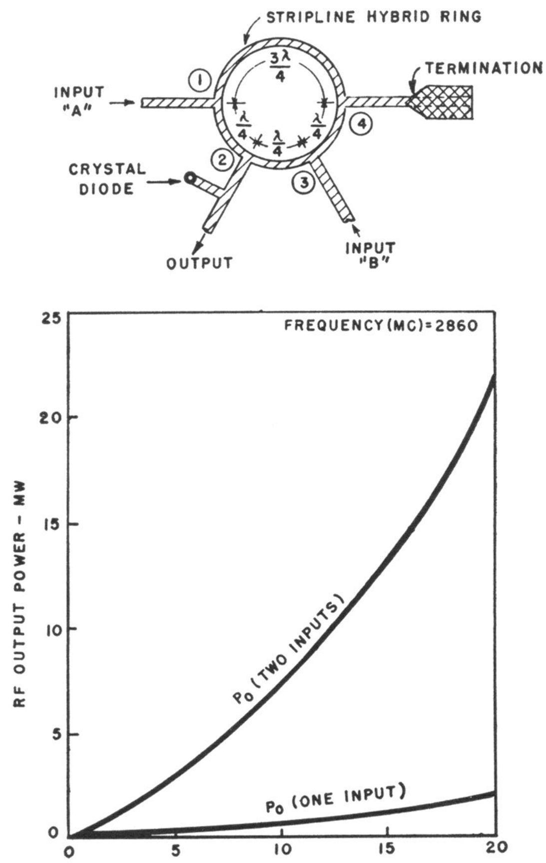


Fig. 5—(a) A stripline AND circuit, using a crystal diode expander circuit; (b) RF performance of AND circuit using a 1N23D crystal diode with 1.5 volts back bias.

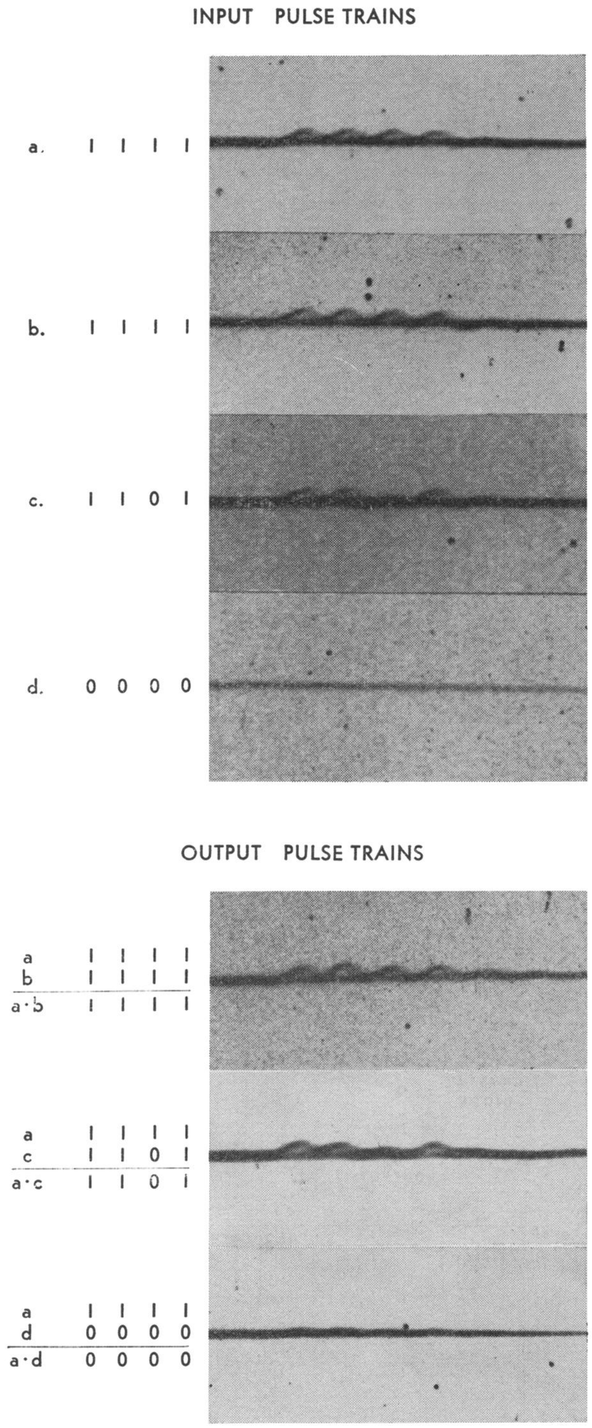


Fig. 6—Oscilloscope tracings illustrating the pulse performance of AND circuit.

performance of the expander at a frequency of 2860 mc. The power transmitted by the expander is plotted as a function of the input power.

Fig. 5(a) shows the construction of the actual AND circuit. An expander is placed in arm No. 2 of a hybrid ring. Arms No. 1 and No. 3 are the input arms, and arm No. 4 is terminated with a resistance card. If only a single input pulse is present, half of its power is absorbed in the termination and the other half appears at the expander. However, if input signals of equal amplitude and phase are applied to both input terminals, they interfere destructively at arm No. 4. In this case no power is lost in the termination, and the signals reinforce one another at the expander. There is, therefore, four times as much RF power incident on the expander as in the case of a single input. Fig. 5(b) shows the CW output power from the AND circuit as a function of the CW input power to a single arm, for one input and for two inputs.

This AND circuit was tested with RF pulses having a duration of slightly less than 2 mμsec. A series of four of these pulses occupied about 8 mμsec. Fig. 6 shows the rectified input pulse trains and the corresponding rectified outputs. Ringing in the circuit is to some extent caused by the modulation, amplification, and demodulation steps required for the oscilloscope display.

Combinations of Basic Circuits: Half-Adders

If the two inputs to a half-adder are denoted as A and B, and the two outputs as SUM (S) and CARRY (C), then the relation between the inputs and outputs is as shown in Table I.[10]

TABLE I
Truth Table for a Half-Adder

A	B	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

The AND circuit shown in Fig. 5(a) can be converted into a half-adder if the termination is removed from arm No. 4 and that arm is made the SUM (S) output. Fig. 7 shows the simple half-adder. The output of the expander is the CARRY (C) output. The characteristics of the SUM and CARRY outputs are similar to those of the NOT and AND circuits of Figs. 2(b) and 5, respectively.

A disadvantage of this simple half-adder is that the phase of the SUM output depends on which of the two inputs is present. It is difficult, therefore, to use this circuit in conjunction with following elements which depend upon the phase of RF. One possible method of reestablishing a fixed phase is shown schematically in Fig. 8. Here, an RF pulse of arbitrary phase is demodulated to produce a dc pulse. This dc pulse, in turn, modulates a CW RF signal to produce an RF output pulse. Thus, the phase of the output RF pulse is independent of the phase of the RF input pulse. In conventional microwave modulators, the resistance of microwave point-contact diodes is varied. Such devices have considerable conversion loss, so an amplifier is required. However, it is possible to build modulators with gain by using variable reactances.[11] In this case, no additional amplification is required.

[11] J. M. Manley and H. E. Rowe, "Some general properties of nonlinear elements—part I, general energy relations," Proc. IRE, vol. 44, pp. 904–913; July, 1956.

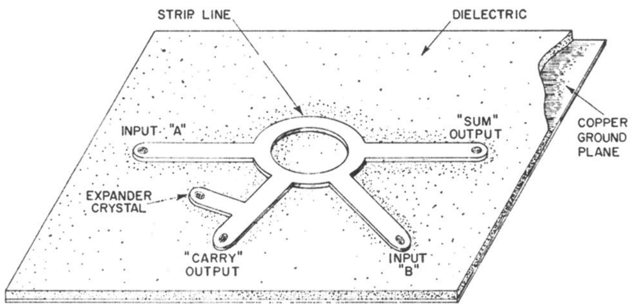


Fig. 7—A half-adder (phase of SUM output not determined).

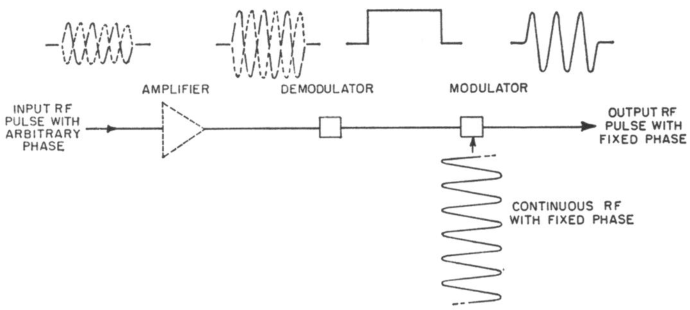


Fig. 8—An amplify-demodulate-modulate circuit for reestablishing a fixed phase of an RF pulse.

It is also possible, however, to build a half-adder in which the phase of the sum output signal is the same regardless of which input signal is present, without resorting to a demodulate-modulate scheme. Such a half-adder is shown schematically in Fig. 9. The RF input signals are divided between two hybrid circuits. The hybrid in the upper left-hand corner simply combines the input pulses. The hybrid in the lower left-hand corner, together with the expander crystal, forms an AND circuit. The output of the AND circuit is split in half. One half appears at the CARRY output terminal. The other half is fed into a third hybrid ring, and arrives at its circumference in phase with the signals from the hybrid in the upper left-hand corner. The adjustable attenuator is set so that these two signals are of equal amplitude when both A and B inputs are present. The third hybrid ring then performs a NOT function to assure that there is no SUM output when inputs are applied to both A and B. The ratios of ONE output amplitude to ZERO output amplitude at the SUM and CARRY terminals are better than 10:1 and 15:1, respectively. Fig. 10 is a photograph of the actual circuit tested; the size of the board is $10\frac{1}{2} \times 10\frac{1}{2}$ inches.

Application to Digital Computers

In applications which require more than a few logic operations, the pulses must be amplified and regenerated at intervals. The amplification could be provided by traveling-wave amplifiers, and the regeneration could be accomplished by using a diode regenerator of the type described by DeLange.[12] Another approach is to use

[12] O. E. DeLange, "Experiments on the regeneration of binary microwave pulses," *Bell Sys. Tech. J.*, vol. 35, pp. 1–23; January, 1956.

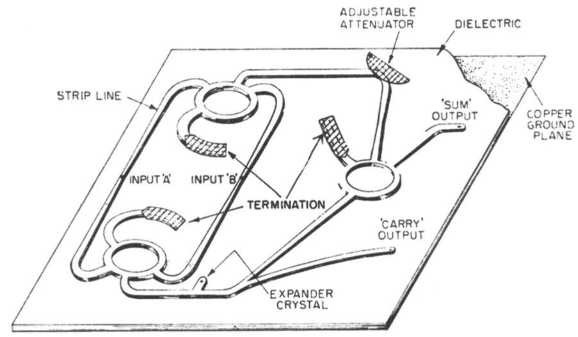


Fig. 9—A phase-determined half-adder.

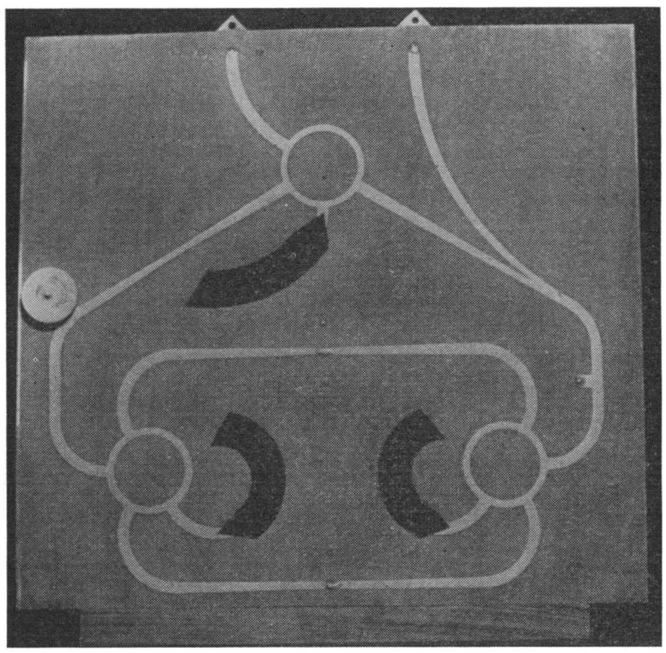


Fig. 10—Photograph of a phase-determined half-adder for use with 3000 mc RF carrier. Coaxial connectors and crystal diode holder mounted on the back of the $10\frac{1}{2} \times 10\frac{1}{2}$-inch board are not visible.

subharmonic oscillators, which amplify and regenerate.[5–7] Although subharmonic oscillators themselves can perform logic operations, some of the logic circuits described in this paper are faster and simpler than corresponding circuits using subharmonic oscillators. It is likely, therefore, that a microwave computer could combine both techniques to obtain the advantages offered by each.

Conclusion

This paper has discussed microwave logic circuits which can perform simple logic functions. In operation with a 3000 mc carrier, the pulse repetition rate is presently limited, by the bandwidth of the components, to about 500 million pulses per second; scaling the components to a higher carrier frequency should make it possible to increase the maximum pulse rate substantially.

Acknowledgment

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