so that[12]

$$l \approx \frac{1-k}{1+k}\,\frac{K^2\epsilon^2}{4} \qquad (\epsilon^2 \ll 1). \tag{31}$$

This can be reduced to a series in q which converges well when q is not too close to unity. It follows from known formulas in elliptic functions and their transformations[13] that

$$\ln K = \ln\frac{\pi}{2} + 4\left(\frac{q}{1+q} + \frac{1}{3}\,\frac{q^3}{1+q^3} + \frac{1}{5}\,\frac{q^5}{1+q^5} + \cdots\right) \tag{32}$$

and

$$\ln\frac{1-k}{1+k} = -8\sqrt{q}\left(\frac{1}{1-q} + \frac{1}{3}\,\frac{q}{1-q^3} + \frac{1}{5}\,\frac{q^2}{1-q^5} + \cdots\right) \tag{33}$$

so that if we write $q = p^2$,

$$\ln\left(\frac{1-k}{1+k}K^2\right) = 2\ln\frac{\pi}{2} - 8\left(\frac{p - p^2 + p^3 + p^4}{1-p^4} + \frac{1}{3}\,\frac{p^3 - p^6 + p^9 + p^{12}}{1-p^{12}} + \cdots\right). \tag{34}$$

[12] Note that higher terms in this expansion are easy to obtain, since (30) is exact.

[13] C. G. J. Jacobi, "Werke," Berlin, vol. 1, pp. 148, 159; 1881.

Thus, expanding a few terms,

$$\ln l = 2\ln\frac{\pi\epsilon}{4} - 8\left(p - p^2 + \frac{4}{3}p^3 + p^4 + \cdots\right), \tag{35}$$

whence

$$l = \frac{\pi^2\epsilon^2}{16}\left(1 - p + \frac{3}{2}p^2 + \frac{5}{2}p^3 + \frac{11}{8}p^4 + \cdots\right)^8 \tag{36}$$

of which the first term again gives (26). The use of (27) and (35) now gives us

$$Z_0 = \frac{30\pi^2/\sqrt{K}}{\ln\dfrac{8H}{\pi(H-C)} + 4\left(p - p^2 + \dfrac{4}{3}p^3 + p^4 + \cdots\right)} \qquad (H - C \ll H) \tag{37}$$

with

$$p = \sqrt{q} = e^{-2D/B} = e^{-\pi D/H}$$

As long as $H - C$ remains less than, say, $H/4$, this is an excellent approximation for any configuration that one would be likely to use in practice.

I should like to express my thanks to Dr. A. Morrison for his helpful suggestions in the preparation of this paper.

A High-Speed Broadband Microwave Waveguide Switch*

W. L. TEETER†

Summary—**A switch which switches microwave energy to any of several separate waveguide loads is described. The switch has the bandwidth and power-carrying capability which is essentially that of the input and output waveguides. Data is given for a switch which operates over the frequency range of 8,600 to 10,000 mc with a vswr of less than 1.15 during transmission and less than 1.5 during switching. The switching speed is limited only by the practical limit for rotating the metal shorting vane. A typical example is given of a 5-output switch with a switching rate of 1,800 per second (vane rotation of 3,600 rpm) and a dead time during switching of 14 per cent of total time. Dead time is a function of switch diameter and vane rotation rate and could be reduced by increasing the vane diameter or rotation rate.**

Introduction

THIS PAPER describes development of a high-speed waveguide switch capable of switching high power from one input to any number of outputs.

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Three types of switches were studied.

The first switch (Fig. 1, next page), places a number of waveguide tees in series. A movable vane, containing a rectangular hole is then moved across the top of each tee to select which load will receive the rf energy. All other loads are shorted. This switch has a 1 per cent bandwidth, excessively high vswr during switching (i.e., 20 to 1), and two rather critical manufacturing tolerances.

The second switch (Fig. 2, next page), has all output waveguides in shunt to provide a turnstile junction. Rf energy enters through the circular waveguide at the base. A cylindrical rotor with a hole in it rotates in such a way that the hole allows energy to pass to a particular load. This switch has a 3 per cent frequency bandwidth, excessively high vswr during switching and two critical manufacturing tolerances.[1]

[1] There is some discussion of the turnstile switch in MIT Rad. Lab. series, vol. 9, p. 538.

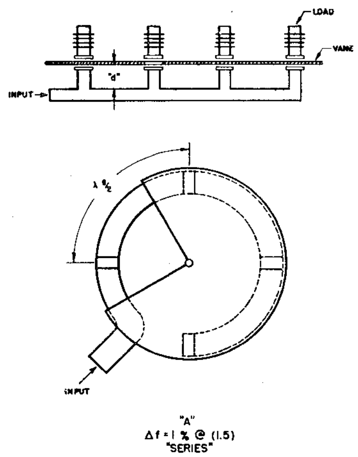

Fig. 1—"Series."

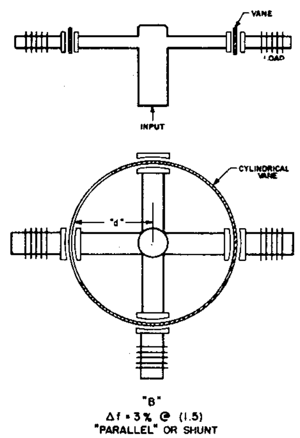

Fig. 2—"Parallel" or shunt.

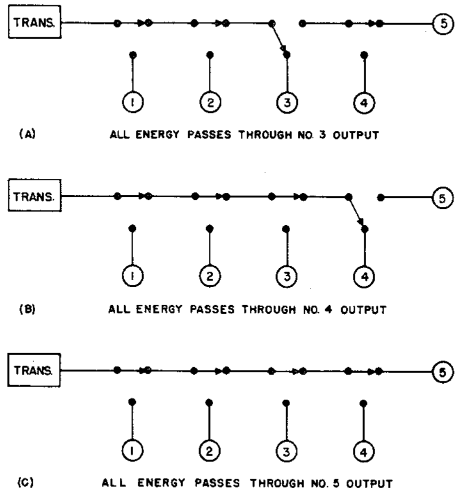

Fig. 3—Switching method.

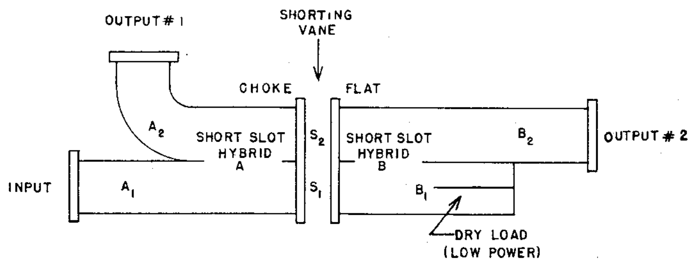

Fig. 4—Block diagram of one switching unit or a two output switch.

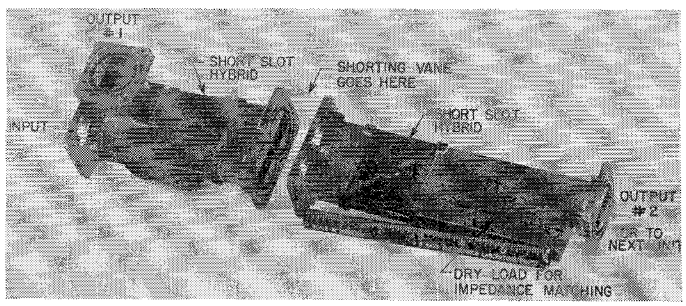

Fig. 5—One switching unit.

The first two switches were discarded because of their narrow frequency bandwidth, high vswr, and high production costs.

The third switch, which eliminates the undesirable features of the first two, will be described in detail. It is termed a hybrid switch since it is made of a series of hybrid junctions. The hybrid switch is diagrammatically explained in Fig. 3, where it is shown as a group of lever arms. Moving lever arm No. 3 to output 3 sends the energy to output 3 as shown in Fig. 3 (a). A lever arm is moved electrically to propagate energy into the desired load. There are no resonant lengths or cavities involved.

The hybrid switch is a configuration of hybrid junctions where each unit is fundamentally a 2-output switch as shown in the block diagram of Fig. 4. RF energy enters the waveguide at the input A_1 and proceeds to the short slot hybrid[2] at A, where the energy splits and proceeds towards S_1 and S_2. If a shorting vane is inserted across S_1 and S_2, all of the energy is reflected and passes out A_2 to output 1. If no shorting vane appears at S_1 and S_2, the energy at S_1 and S_2 proceeds down to the second short slot hybrid junction at B, where *all* energy recombines to proceed past B_2 and into output 2 or the next unit. Thus the rf energy may be changed from output 2 to output 1 by the insertion of a shorting vane at S_1 and S_2.

When a shorting vane is present at S_1 and S_2, *none* of the energy returns to A_1 because of the hybrid junction action. Similarly, when no shorting vane is present, all energy passing S_1 and S_2 recombines in the hybrid junction B to flow into output 2. None of the energy returns to branch A_1. A *low power* dry load is placed at B_1 to properly terminate branch B_1 and absorb any small amount of energy due to any misbalance of hybrid B. In normal practice the unbalance of the hybrid junction is slight enough so that the energy in B_1 is at least 30 db below the energy in branch B_2.

Fig. 5 is an actual photo of a single switching unit.

[2] H. J. Riblet, "The short-slot hybrid junction," Proc. IRE, vol. 40, pp. 180–184; February, 1952.

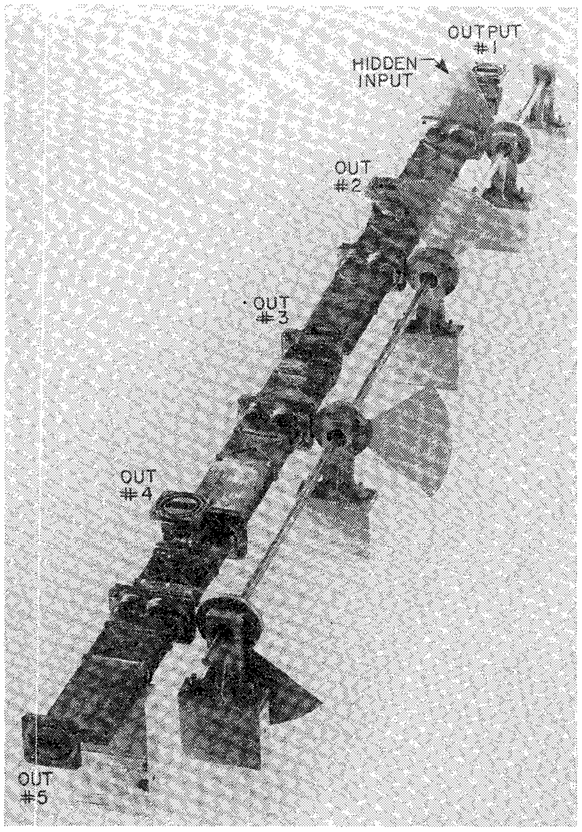

Fig. 6—Bench model test switch.

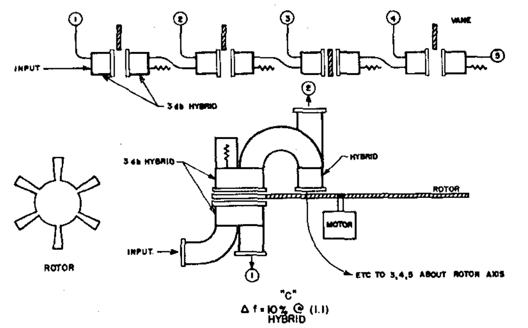

Fig. 7—Hybrid.

A particular switch can be made of a collection of as many units as may be necessary to obtain the desired outputs.

Fig. 6 shows the first bench model of the hybrid switch. It contains four basic units, as shown in Fig. 5, and has five outputs, It also contains a rotating vane, and a motor on a shaft. The switch, as shown in Fig. 6, is sending all energy into output 1.

If several hybrid junctions are arranged in a circular configuration, a single rotating vane as shown in Fig. 7 can be used to make the switch be a compact package as shown in Fig. 8. This switch is about 9 inches in diameter and about 8 inches high. The rotor has six vanes of 16 degrees width each. When the rotor speed has reached 3,600 rpm, 1,800 switchings per second are obtained.

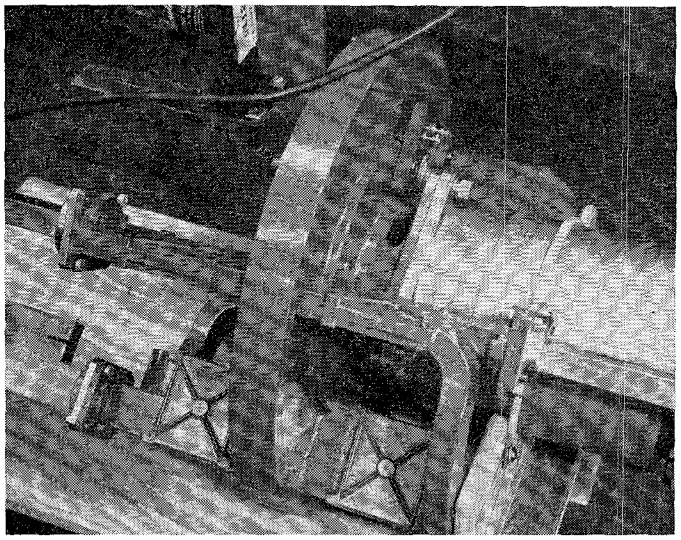

Fig. 8—Circular switch (5 outputs).

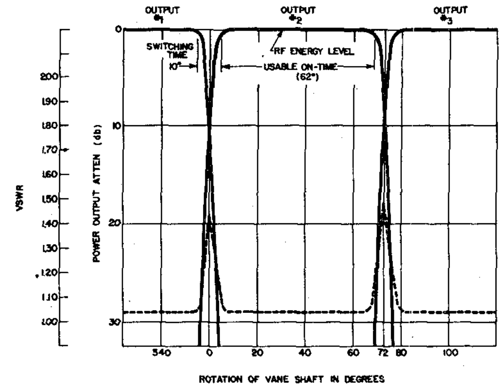

Fig. 9—Graph of switching time (attenuation and vswr vs. angle or time).

Characteristics and Test Results (Bench Model Switch)

Tests were conducted using a standard 0.5-by-1-by-0.050-inch waveguide test bench with standard procedures.

Switching Time

Fig. 9 shows electrical switching time or angle vs attenuation. The energy level at output 1 is shown first, then switched to output 2, then to 3, etc. Only three of the output levels are shown since they are repetitive. With full energy at output 1, the rotor is rotated until the shorting vane enters the gap after output 2. As the rotation continues, the energy to load 1 is reduced more than 30 db and at the same time all output is switched to load 2. As Fig. 9 shows, the energy in output 2 is within 1 db of full energy for 62 degrees of rotation. Ten degrees of rotation are needed for switching from one output to another. The vane completely covers the waveguide opening for less than 62 degrees of rotation, but the waveguide is effectively shorted for the full 62 degrees because the vane acts as a nonresonant iris before it completely covers the waveguide opening. A vane of 72 degrees was used on the bench model test switch.

The dashed line of Fig. 9 shows the vswr as a function of angle of rotation.

VSWR and Bandwidth

Fig. 10 shows total vswr vs frequency, measured at the input, for each output from 1 through 5. Curves for outputs 2, 3 and 4 lie between curves for outputs 1 and 5 and for simplicity are not shown in the figure.

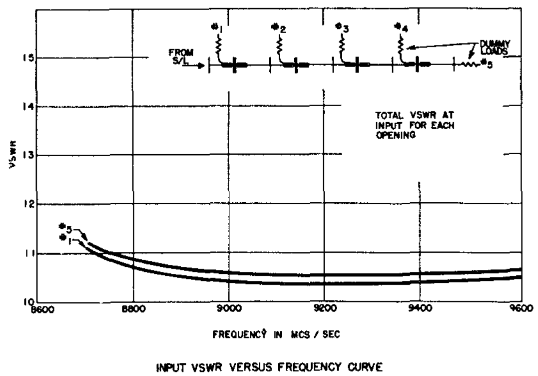

Fig. 10—Input vswr vs frequency curve.

Fig. 11 shows insertion loss of each unit vs frequency. Insertion loss for output 5 is below the nominal 0.05-db figure of the other outputs, since it is merely the output of unit 4.

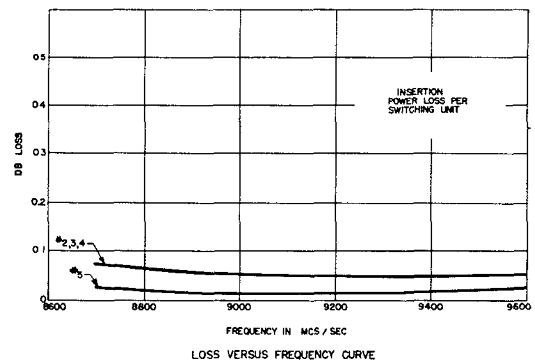

Fig. 11—Loss vs frequency curve.

In use, any number of units may be connected in series to provide a desired number of outputs. Each added unit increases the insertion loss by approximately 0.05 db. Thus, one may expect a difference of 0.1 db in output level between load number one and load number three. However, by rearranging the units in series-parallel arm combinations this output variation can be eliminated. The switches shown in Figs. 6, 7 and 8 are single pole, five throw.

Dead Time Information

In order to obtain maximum on-time and minimum dead time (switching time) one must consider all operating parameters for a particular switch. Fig. 12 is a plot of the time necessary for the vane to cover the waveguide opening as the rotor rotates at given speeds for a particular set of parameters. The set of parameters used was for 2,000 switchings per second into five outputs. Any change in the operating parameters would necessitate a new plot. However, examination of the curves shows a 25 per cent dead time curve (300 μsec on time), a 50 per cent dead time curve (200 μsec on time), etc. Note that the dead time (switching time) can be reduced to a very low percentage if the vane radius is large for reasonable rotor speeds. The analysis in Fig. 12 is by trigonometry.

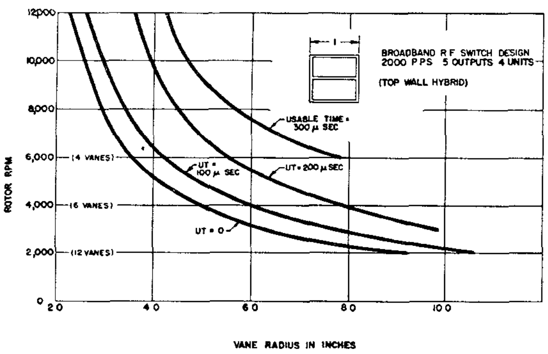

Fig. 12—On time plot for rpm vs radius.

Conclusions

A broadband waveguide switch was developed with the following characteristics:

1) The final switch presented a maximum vswr of 1.1 from 8,900 to 9,600 mc during "on time," and 1.4 during switching.

2) The switch can be made from four lightweight, inexpensive, preselected components, making low-cost construction possible. No impedance matching is necessary.

3) The tight mechanical tolerances of other types of switches are practically eliminated in this switch and need be no better than that of conventional waveguides.

4) The dimensions can easily be scaled to any size waveguide for a similar switch. Furthermore, any number of units may be used to obtain any desired number of outputs.

Acknowledgment

The author is indebted to Mr. K. R. Bushore, who performed most of the test bench measurements and to Mr. H. Berland who made many helpful suggestions.