where the sign which must be set as the real part of P_m becomes positive. The stability condition is given as follows, using (39)

$$|A_m + D_m| \leqq 2. \quad (40)$$

When the unit section has a symmetric property in the axial direction and the elements of the $\tilde{F}$ matrix of the first half section are A_h, B_h, C_h, and D_h, then

$$P_m = \sqrt{A_h B_h / C_h D_h} \quad (41)$$

and the stability condition is as follows,

$$A_h B_h C_h D_h \leqq 0. \quad (42)$$

ACKNOWLEDGMENT

The authors wish to thank Prof. M. Kawakami, Prof. M. Nishimaki, Prof. K. Suetake, and Prof. T. Sekiguchi of Tokyo Institute of Technology for their useful advice and encouragement. Also gratefully acknowledged are H. Fukinuki, who gave illuminating suggestions and discussions, and I. Obata and S. Kosaka, who helped conduct experiments.

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A Switching Circulator: S-Band; Stripline; Remanent; 15 kilowatts; 10 microseconds; Temperature-Stable

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Abstract—A stripline, three-port remanence circulator switch has been designed for high-speed switching of time delay in a phased array radar at S-band (2.9 GHz). Special attention was devoted to minimizing switching time and energy through design of the magnetic circuit and suppression of eddy currents. Temperature stabilization of insertion phase was accomplished by means of a flux regulating magnetic circuit. Switching performance: time: less than 10 microseconds; energy: 450 microjoules. Circulator performance: bandwidth for >26 dB isolation, 8.9 percent; insertion loss, 0.35 dB. Temperature stability of insertion phase: one electrical degree per 10°C. Peak RF power: 15 kW. The discussion includes details of the junction design and performance, techniques of eddy current suppression, temperature stabilization, and the method of switching energy measurements.

Manuscript received July 1966.
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INTRODUCTION

THIS PAPER reports the development of a ferrite switching circulator suitable for time delay switching applications in phased array radars. The re-

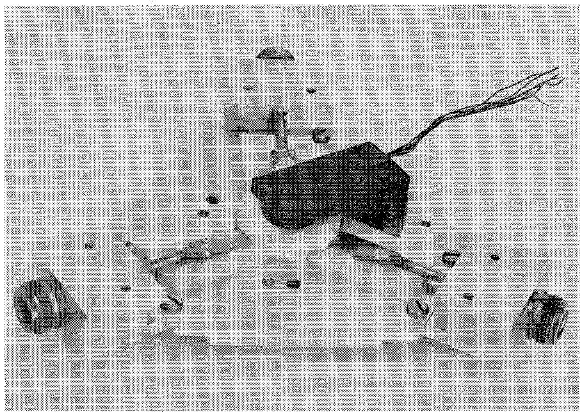

Fig. 1. Interior of switching circulator.

TABLE I

Frequency	2.90 GHz
Input impedance level	50 ohms
Stripline ground plane spacing	0.250 inch
Ferrite: saturation magnetization	400 gauss
remanent magnetization	240 gauss
dielectric constant	14
ΔH (X-band)	60 oersteds
Ferrite disk diameter	0.705 inch
Matching transformer impedance	33 ohms

quirements are high speed and minimum switching energy, combined with good isolation and match, and low insertion loss over a moderate band. Stability of transmission phase is also an important requirement. Performance must be maintained in the presence of changes in operating conditions such as ambient temperature, RF power, and switching rate. Data are presented here on design considerations, performance, and methods of measurement.

To the best of the authors' knowledge the first latching circulator in TEM transmission line to achieve good microwave performance was built by Western Microwave Laboratories, Inc. [1]. This device operated the ferrite at a high dc magnetic bias with consequent high switching energy. In the present device the ferrite is operated at essentially zero internal field with consequent reduction of switching energy. Good temperature stability is maintained with a flux regulating magnetic circuit.

I. Circulator Design

The circulator design is based on the work of Bosma [2] as further developed by Fay and Comstock [3] with the modification that the ferrite is operated in the remanent state. The circulator with the top ground plane removed is shown in Fig. 1 to illustrate the microwave construction. The design is conventional with a circular center conductor, ferrite disks between it, and the ground plane and dielectric rings which form the quarter-wave matching transformers. A summary of the design is given in Table I.

TABLE II

Frequency	2.90 GHz
Maximum isolation	>40 dB
Bandwidth at 26-dB isolation	240 MHz (8.9 percent)
VSWR at 26-dB isolation	1.11
Minimum insertion loss	0.35 dB
Switching time	<10 μs (see text)
Switching energy delivered to the circulator	450 μJ
Temperature variation of transmission phase	1° phase per 10°C (to 60°C)
Average power capability (Dielectric melted at 400 watts)	300 watts (water cooling)
Peak RF power capability (RF arcing at 40 kW)	15 kW (0.1-dB rise in insertion loss)

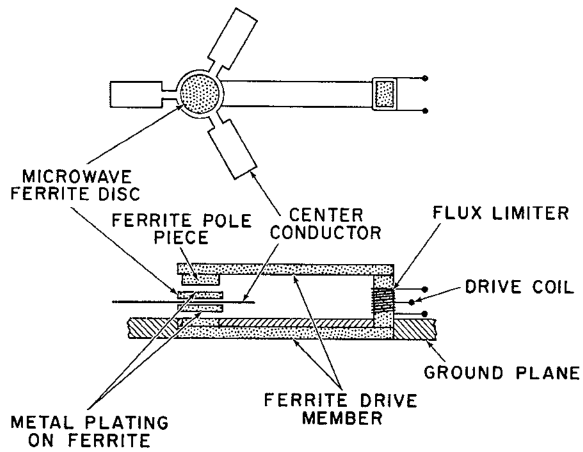

Fig. 2. Details of magnetic circuit.

A preliminary test model with copper center conductor was built to verify the design. It was operated with an electromagnet, giving an insertion loss of 0.15 dB and a bandwidth of 200 MHz, at a flux density of 210 gauss. In the final design, incorporating an integral magnetic yoke and operating at remanence, the higher resistivity conductors used to achieve good switching performance raised the insertion loss to 0.35 dB and the bandwidth to 240 MHz. The microwave and switching performance is summarized in Table II.

In defining switching time, it is important to consider the special requirements of the phased array application. Since insertion phase is the most crucial parameter, the appropriate definition is the time required for the phase of the transmitted signal to reach within a specified tolerance of its steady-state value. For an arbitrarily chosen $\pm 2°$ tolerance, the switching time is found to be less than 10 microseconds. The device can be switched somewhat faster but with considerable increase in switching energy.

II. Magnetic Circuit

Details of the magnetic circuit are shown in Fig. 2. The magnetic circuit is brought through the ground planes by cylindrical pole pieces and the magnetic circuit completed outside the ground planes. The center conductor is photoetched out of 0.5 mil stainless steel with those portions outside the magnetic circuit copper plated to reduce microwave loss. Surfaces of the ferrite disks near the ground planes are plated with 0.2 mils of tin to maintain RF continuity across the ferrite pole pieces. Thickness (somewhat more than a skin depth) and resistivity of the platings are such that eddy currents are kept small with only moderate microwave loss. The ground plane is slit from the pole piece to the flux limiter so that it will not act as a shorted turn linking the switched flux. The ferrite platings are insulated from the ground planes with 0.5 mil FEP teflon film to preserve the open circuit for eddy currents created by the slot.

III. Temperature Stabilization

Temperature stability of the circulator is obtained through the flux regulating properties of the magnetic circuit. The principles and design of such circuits have been described by Stern and Ince [4] and will only be reviewed briefly. Referring to Fig. 2, the magnetomotive force necessary to maintain flux in the microwave ferrite is supplied by the drive members. In operation of the circuit these members are driven on a minor hysteresis loop. Ferrite material chosen for these pieces need not have good microwave properties but should have square hysteresis loop and coercive force that varies little over the operating temperature range. The drive coil is wound on the flux limiter which is of such cross-sectional area that it is driven on a major loop and sets the peak flux level in the circuit. Therefore the material chosen for the limiter should have a saturation magnetization that varies little over the operating temperature range. With the majority of the MMF supplied by a temperature-stable square loop material and the peak flux set by the temperature-stable limiter, dependence of the operating flux on properties of the microwave material is greatly reduced.

The degree of temperature stabilization afforded by the flux regulating magnetic circuit is indicated in Figs. 3 and 4. Figure 3 shows remanence flux, normalized to the room temperature value, both for a toroid of the microwave ferrite and for the flux regulating circuit. As the remanence magnetization in the microwave material tends to drop sharply, the driver ferrite supplies additional MMF to maintain the net flux at a high level. At 100°C the flux has fallen to 85 percent of the room temperature value, a variation which is essentially due to the variation of $4\pi M_s$ of the limiter ferrite. Near the Curie temperature of the microwave material, the driver loses control and the flux drops rapidly.

The extent to which the microwave performance has been stabilized is shown in Fig. 4. Bandwidth for 26 dB isolation is plotted vs. temperature, showing essentially constant bandwidth up to around 55°C. At 65°C the bandwidth has fallen to 80 percent of the room temperature value and falls off very rapidly above about 70°C.

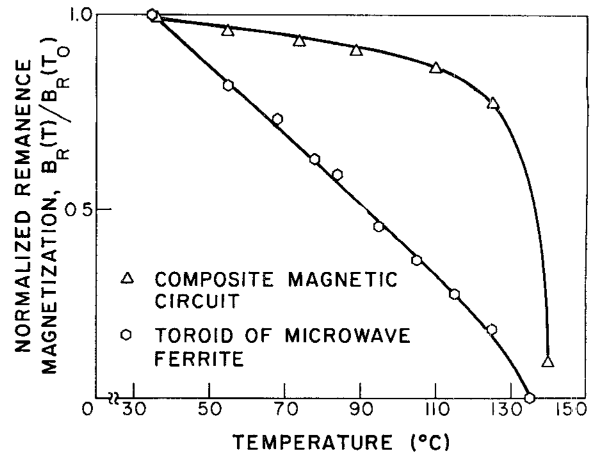

Fig. 3. Remanence flux vs. temperature.

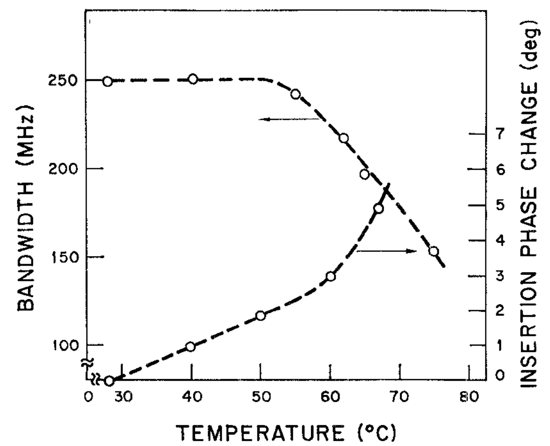

Fig. 4. Microwave performance vs. temperature.

The variation of insertion phase is also shown with changes of about 1° phase per 10°C temperature change up to 60°C where it begins to vary much more rapidly.

IV. Eddy Current Evaluation

The magnetic circuit used to evaluate eddy current effects is shown in Fig. 5. There are two pick-up coils on the pole pieces, one at the base of the bottom pole piece, which is linked by flux that closes around the whole circuit, and a second at the face of the upper pole piece near the metal surface being tested. A large drive current is applied to the coil on the left member, switching the circuit rapidly. Since the left member is virtually saturated by the drive, the flux due to eddy currents closes chiefly near the metal. Since this flux cannot be controlled by the drive, circulator performance will not stabilize until eddy currents have died out. The voltages from the two coils are subtracted and integrated to give a voltage proportional to eddy current flux. The eddy current time constant for the tin platings and for the stainless steel center conductor was found with this device to be of the order of 3 microseconds or less.

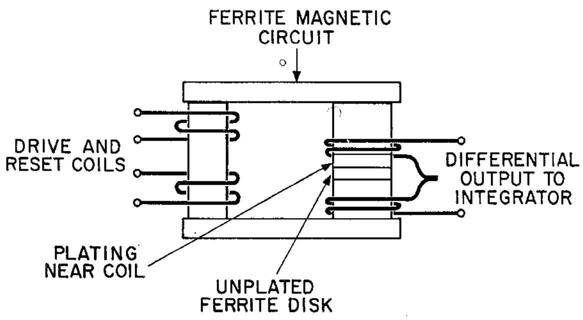

Fig. 5. Eddy current test circuit.

V. Switching Energy Measurement

A method of measuring switching energy was used, which gives accurate results and is faster and more convenient than the usual method; viz., integrating the product of the time-dependent voltage and current.

The switching energy measurements are made from flux vs. MMF loops of the magnetic circuit as follows. Referring to the equivalent circuit of Fig. 6, switching energy is defined as

$$W_s = \int_0^{T_s} eidt = \int_0^{T_s} \left(N\frac{d\phi}{dt} + L\frac{di}{dt} + Ri\right) idt.$$

T_s is switching time, L is leakage inductance, and R is the resistance of the drive circuit. Since the initial and final values of current are zero, and R is generally negligible, there remains only the term

$$W_s = \int_0^{T_s} N\left(\frac{d\phi}{dt}\right) idt = \int_{\phi_1}^{\phi_2} Nid\phi.$$

Referring to Fig. 6 and thinking of an integral as the area under a curve, it can be seen that the value of the integral is equal to the area bounded by the ϕ vs. Ni curve and the ϕ axis. That is, W_s equals half the area of the flux-MMF loop.

The loss contribution of magnetic hysteresis can be distinguished from that due to eddy currents by comparing ϕ-MMF loops obtained under pulsed switching with those observed at low frequencies. Several pulsed loops are illustrated in Fig. 7; the three frames show flux vs. applied MMF when eddy currents are absent, moderate, and severe, respectively. Switching time is approximately 10 microseconds. For the present circulator, the switching energy of 430 microjoules is composed of a magnetic hysteresis loss of 130 microjoules and an eddy current loss of 300 microjoules.

The equipment used to generate pulsed hysteresis loops is shown in Fig. 8. The pulse current is sensed with a Tektronix current probe and the flux signal is generated by means of a Tektronix-type "O" operational amplifier used as an integrator. The loop display is photographed and the area measured with a planimeter.

VI. Peak Power Effects

At sufficiently high RF peak power, the insertion loss of the circulator increases above the low power value

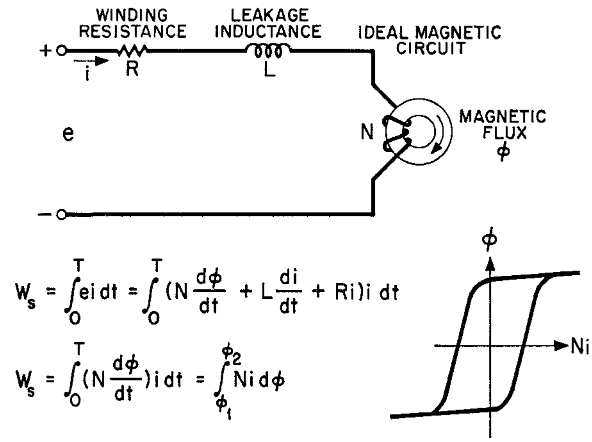

Fig. 6. Equivalent circuit, switching energy measurement.

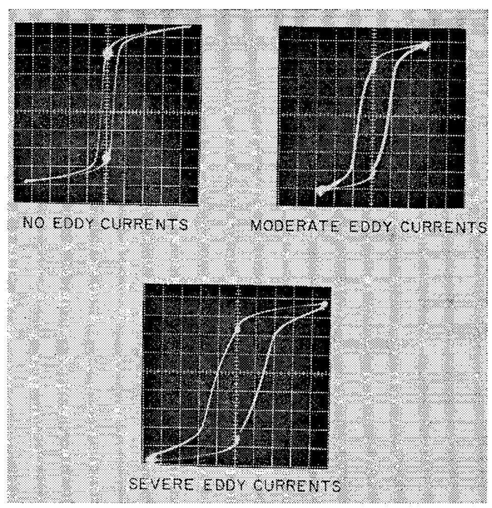

Fig. 7. Pulsed hysteresis loops showing eddy current effects.

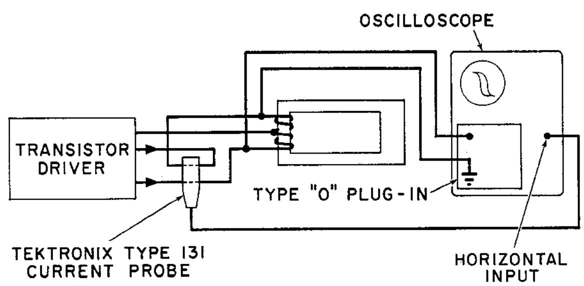

Fig. 8. Equipment to generate pulsed hysteresis loops.

due to nonlinear effects. Although in general the loss begins to rise at a more or less well defined power level, with certain ferrite materials the device can be operated considerably above this level with only modest increase in loss. Insertion loss vs. peak power data for the circulator with several different materials is shown in Fig. 9. The performance specified in Table II was obtained with a commercially available material having $4\pi M_s = 400$ and $\Delta H = 60$ Oe. It gives an increase in loss of 0.1 dB at 15 kW, and at 24 kW the insertion loss rise is about 0.2 dB. An experimental material with $4\pi M_s = 425$ and $\Delta H = 104$ gave a smaller rise in insertion loss at high power, but the loss at low power was higher by about 0.05 dB.

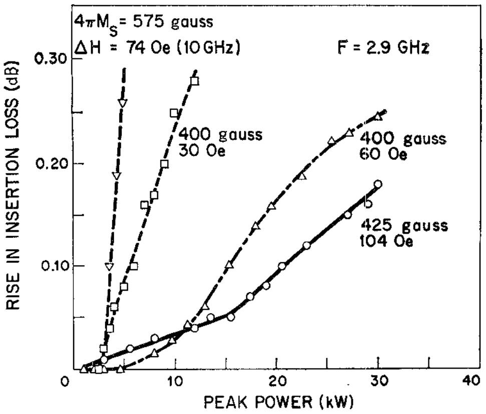

Fig. 9. Rise in insertion loss vs. peak power.

Acknowledgment

The interest of and helpful discussions with E. Stern are gratefully acknowledged.

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A 35-GHz Latching Switch

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Abstract—**The development of a fast switching, small, lightweight latching three-port ferrite circulator is outlined. Geometrical configurations, as relating to the toroidal ferrite element and their apparent effects on operating characteristics, are presented.**

Considerations relating to the proper selection of ferromagnetic materials, compatible with latching applications, are discussed. The finalized device operates at 35 GHz with an instantaneous bandwidth of 5 percent. Total weight is less than 0.6 oz, while total volume is less than 0.750 cubic inch.

Performance characteristics are presented, showing a maximum insertion loss of 0.50 dB and a minimum isolation of 15.0 dB, while switching times of less than 0.3 μs have been achieved (under dynamic operating conditions). The unit exhibits highly stable characteristics over the temperature range of −60°C to +100°C.

Introduction

This paper describes the development of a lightweight, fast switching, 35-GHz latching ferrite circulator, with an instantaneous bandwidth of 5 percent and switching time of less than 0.30 μs. The device is designed for use over the temperature range of −60°C to +100°C under dynamic operating conditions.

This latching circulator is particularly well suited for use as a switching element in applications where high reliability, small size and weight, and fast switching time are required. Total weight of the device is less than 0.60 ounce, and total volume is less than 0.75 cubic inch (see Fig. 1).

Manuscript received May 31, 1966; revised September 6, 1966.

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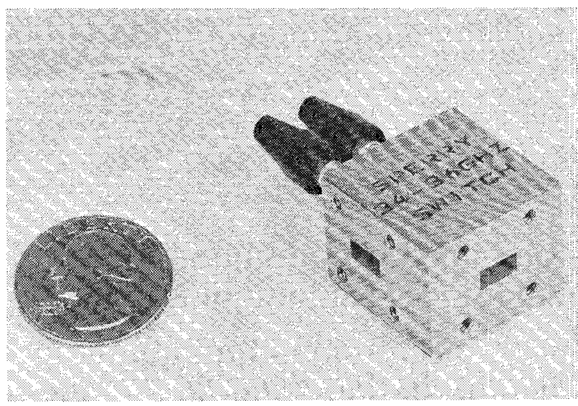

Fig. 1. 35-GHz latching switch.

Design Considerations

Three-port junction circulators using externally applied magnetic biasing fields have been reported by a number of investigators [1]–[5]. Application of these devices as switching elements requires the use of cumbersome electromagnets, application of continuous holding power, and closely regulated power sources. In addition, these devices have been too slow for many proposed RF switching applications.

The use of latching ferrite elements in the construction of an S-band differential phase-shift circulator has been described by Levy and Silber [6], while more recently, the novel application of latching ferrites to Y-junction circulators has been reported by Goodman [7],