X-4. A SWITCHING CIRCULATOR: S-BAND; STRIPLINE; REMANENT; 10 KW; 10 MICROSECOND; TEMPERATURE-STABLE

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Introduction. This paper reports the development of a ferrite circulator-switch suitable for time delay switching applications in phased array radars. The requirements 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 against temperature variations is an important requirement, especially in large arrays. Data will be reported here on design considerations, performance, and methods of measurement.

Circulator Design. The junction circulator configuration is based on the work of Bosma[1] as further developed by Fay and Comstock.[2] The design procedure is modified slightly for operation with the ferrite in the remanent state. For an S-band array the design is in stripline, consisting of circular discs of composite ferrite-dielectric arranged on a circular center conductor and provided with quarter-wave transformers matching to 50 ohm line. A summary of the design is given in Table 1.

TABLE 1

Frequency	2.70 GHz
Input impedance level	50 ohms
Stripline ground plane spacing	0.250 in
Ferrite: saturation magnetization	400 gauss
remanent magnetization	240 gauss
dielectric constant	14
Ferrite disc diameter	0.705 in
Matching transformer impedance	33 ohms

A preliminary test model, built to verify the design, 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 (Fig. 2) 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 300 MHz. The microwave and switching performance is summarized in Table 2.

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TABLE 2

Frequency	2.70 GHz
Maximum isolation	40 db
Bandwidth at 26 db isolation	240 MHz (8.9%)
VSWR at 26 db isolation	1.11
Minimum insertion loss	0.35 db
Switching time (defined in the text)	10 μsec
Switching energy delivered to the circulator	450 μjoules
Temperature variation of transmission phase	1^{o} per 10^{o}C
Peak r-f power capability (R.F. arcing at 20 kw)	15 kw

In defining switching time, it is important to take account of the special requirements of the phased array application. Since insertion phase is the significant 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. Thus, for a tolerance of $\pm 2^{o}$, and assuming the most unfavorable combination of phases, switching is accomplished only when the isolation reaches 30 db. In accordance with this criterion, the switching time is slightly less than 10 microseconds.

Eddy-Current Suppression. In order to achieve this speed with reasonable switching energy, the design incorporates thin conducting surfaces for suppression of eddy currents. Figure 1 shows the magnetic circuit with metal center conductor and thin metal plating on the ferrite discs to maintain r-f continuity at the ground plane. The ferrite discs are plated with 0.00015 inches of tin and insulated from the ground plane by a thin film of silicone varnish. Stainless steel foil 0.0005 inches thick was used for the center conductor, with the portion outside the magnetic circuit copper-plated to reduce microwave loss. With this construction the time constant for decay of eddy currents was less than 8 microseconds.

In addition to limiting the switching speed, eddy currents also contribute to the switching energy. An estimate of the magnetic contribution (hysteresis loss) to the switching energy is 130 microjoules; with additional energy absorbed by the eddy currents, the total energy delivered to the circulator is 450 microjoules.

It should be emphasized that these data on switching energy and speed relate to a structure designed for S-band. Volume of ferrite (hence hysteresis loss) and area and skin depth of conductor (hence eddy current loss) decrease rapidly with increasing frequency of operation.

Temperature Stabilization. The performance of the circulator must be stable against variations in temperature which arise from a number of sources, including heat generated within the device due to r-f power absorption, eddy currents, and hysteresis loss, as well as ambient conditions. The relative importance of these factors depends on such system considerations as average r-f power level and repetition rate. Temperature-stable operation of the magnetic circuit was obtained by using the composite circuit method of Stern and Ince.[3] Referring to Fig. 1, the flux limiter is driven on its major hysteresis loop to set the peak flux. A material was used whose saturation magnetization remains stable over the operating temperature range. The driver members are operated on a minor loop and supply MMF to maintain a constant remanence flux level in the microwave material. The driver ferrite was chosen to have very square minor loops and little variation in coercive force over the operating range.

Figure 3 is a plot of normalized remanence magnetization versus temperature for a toroid of the microwave material alone and for the composite circuit, showing the improvement in flux stability. The corresponding variation in insertion phase of the circulator is less than one electrical degree per ten degrees centigrade for temperatures up to 60°C.

Hysteresis Measurements. Switching energy measurements were made from B-H loops (actually flux-MMF loops) of the composite magnetic circuit. Switching energy is defined as

$$W_s = \int_o^T ei\,dt = \int_o^T (N\frac{d\phi}{dt} + L\frac{di}{dt} + Ri)i\,dt \qquad (1)$$

T is switching time, L is stray inductance, and R is resistance of the drive circuit. Since the initial and final values of current are zero, and since R is negligibly small, there remains only

$$W_s = \int_o^T (N\frac{d\phi}{dt})i\,dt = \int_o^T Ni\,d\phi \qquad (2)$$

This is half the area of the ϕ-MMF loop which is easily measured with a planimeter. Alternatively, the product ei may be formed and integrated graphically; agreement is within 10%.

The loss contribution of hysteresis can be distinguished from that due to eddy currents by comparing ϕ-MMF loops obtained under pulse switching with those observed at low frequencies. Loops taken under pulsing are illustrated in Fig. 4; the three frames show flux versus applied MMF when eddy currents are absent, moderate, and severe, respectively. Switching time is approximately 10 microseconds. These loops were made using a Tektronix Type "0" operational amplifier as an integrator, with a Tektronix Type 131 current probe for current (MMF) sensing.

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References

1. H. Bosma, "On Stripline Y-Circulation at UHF," IEEE Trans. PGMTT 12, 61 (January 1964).

2. C. E. Fay and R. L. Comstock, "Operation of the Ferrite Junction Circulator," IEEE Trans. PGMTT 13, 15 (January 1965).

3. E. Stern and W. J. Ince, "Temperature Stabilization of Unsaturated Microwave Ferrite Devices," Eleventh Conf. on Magnetism and Magnetic Materials, San Francisco, paper F6 (November 1965).

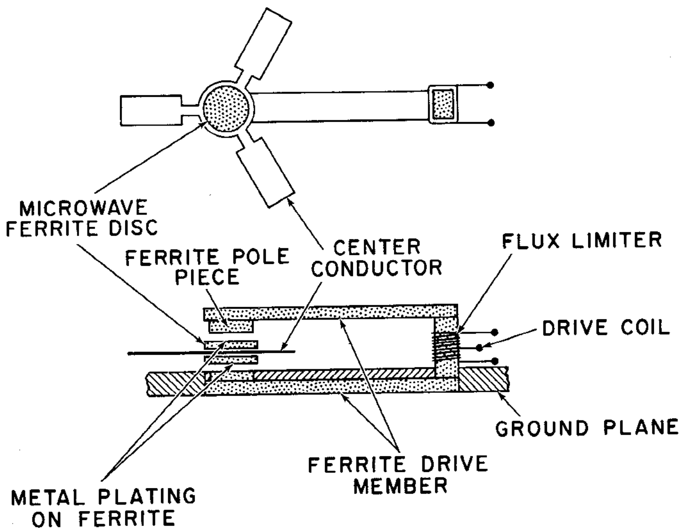

Figure 1. Circulator Magnetic Circuit

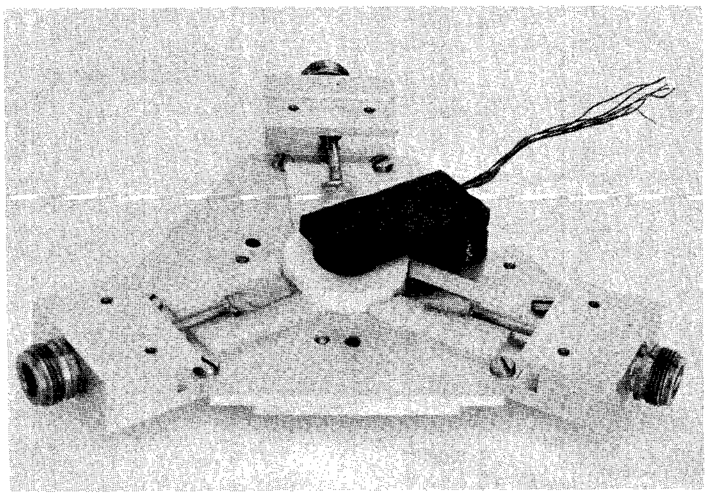

Figure 2. S-Band Switching Circulator

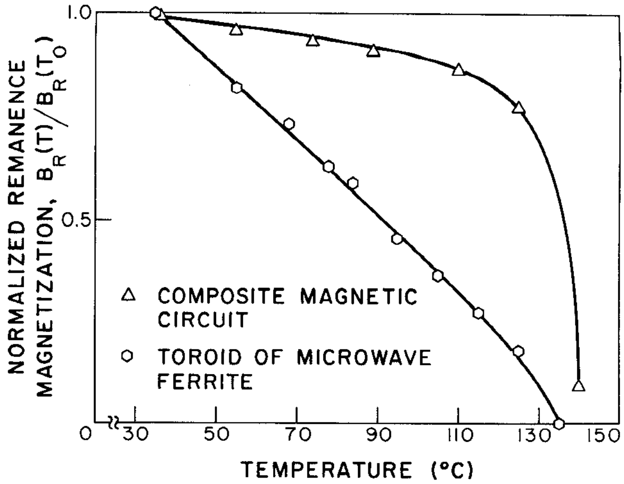

Figure 3. Normalized Remanence Magnetization vs Temperature

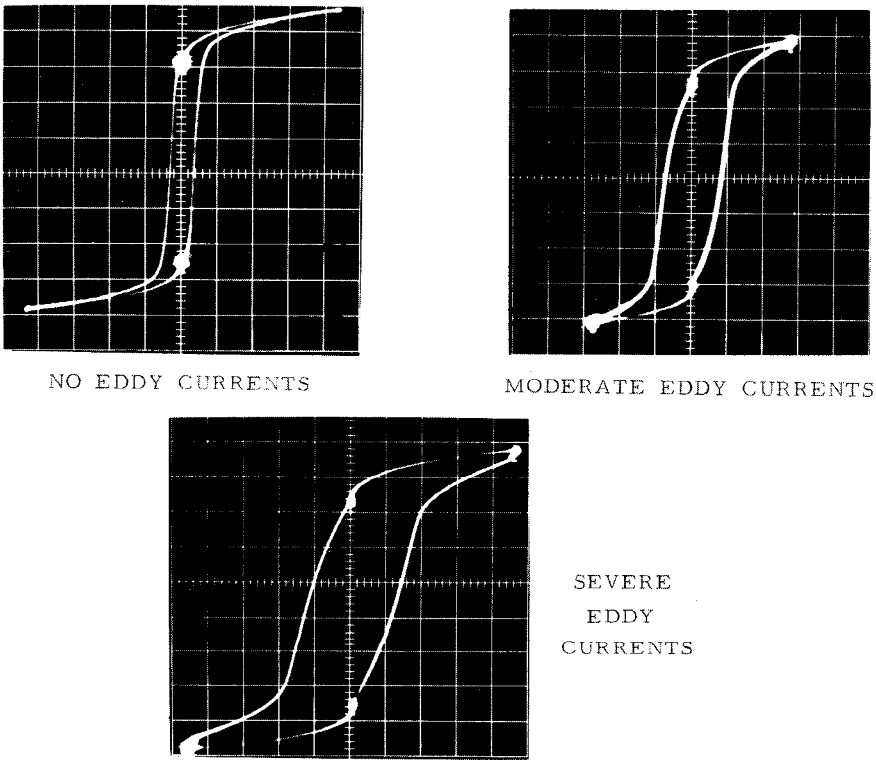

Figure 4. Pulsed Hysteresis Loops Showing Eddy Current Effects