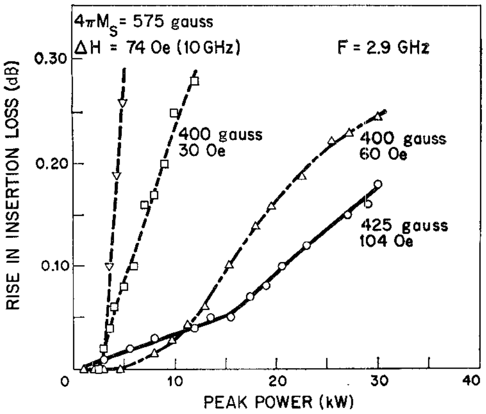

Fig. 9. Rise in insertion loss vs. peak power.

Acknowledgment

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

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A 35-GHz Latching Switch

W. C. PASSARO, MEMBER, IEEE, AND J. W. McMANUS, MEMBER, IEEE

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).

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The authors are with the Sperry Microwave Electronics Company, a division of the Sperry Rand Corporation, Clearwater, Fla.

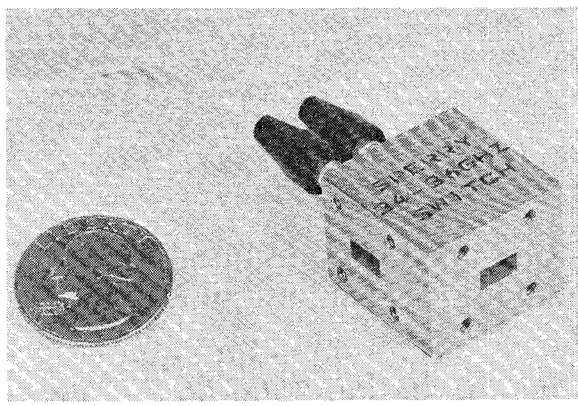

Fig. 1. 35-GHz latching switch.

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],

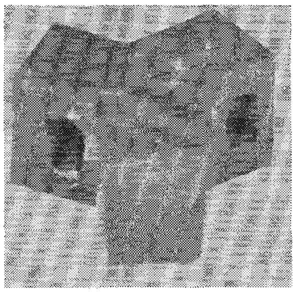

Fig. 2. Three-port latching element (similar to the design used by Goodman).

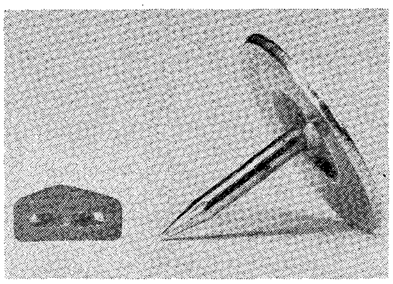

Fig. 3. Triangular ferrite latching element used in 35-GHz switch (size can be compared to normal size thumb tack).

The waveguide junction circulator, which Goodman has described, uses a ferrite toroidal structure similar to the one shown in Fig. 2, which is the microwave RF ferrite element and complete magnetic circuit combined. This general type of construction overcomes the disadvantages inherent in devices using externally applied biasing fields.

The latching V-band circulator described in this paper also utilizes an internal ferrite toroidal structure, but of a different design than that of Goodman's. The ferrite is constructed basically in the shape of a triangular prism as shown in Fig. 3.

The main advantage in using the triangular shaped latching element is that it appears to exhibit better broadband characteristics. The element is positioned so that its pointed edges are in the center of the waveguide and, as suggested by Fay and Comstock [5], are regions of nearly linear polarization and as such act more like dielectric tapers rather than ferrimagnetic material.

Circulator Design

The basic design considerations of the junction circulator is based on the work of Bosma [4], as further extended by Fay and Comstock [5]. Minor modifications in the design procedure are incorporated to allow for operation in the remanent state, since the remanent magnetization of the material appears to provide the necessary magnetic biasing of the ferrite.

The selection of materials was initially guided by conventional design criteria, as relating to three-port junction circulators [9]. Though these materials exhibited satisfactory results when using external magnetic biasing field, they behaved rather poorly when used as latching elements. Therefore, it was necessary to improve the hysteresis properties of the material. This was accomplished by improved processing techniques, during the preparation of the material. The final material chosen for this device was a nickel-zinc-manganese-ferrite with a remanence ratio (R_r) of 0.52 and a coercive force (H_c) of 0.90 oersted.

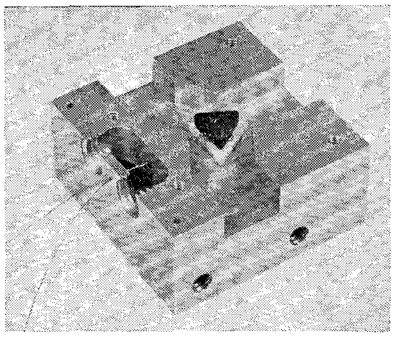

Fig. 4. Bottom half of waveguide junction showing ferrite element with charging wire.

The latching ferrite element, which occupies a volume of 0.024 cm^3, is shown in Fig. 4, positioned in place by rigid Styrofoam triangular spacers, directly above and below it. The physical shape and size of these spacers, as well as the RF characteristics of the material used, were arrived at empirically. In addition to acting as positioning devices, these pieces also perturb the junction characteristics so as to aid in the impedance matching of the device.

The element shown in Fig. 4 is designed to provide a closed magnetic path entirely within the material. The charging wire, which carries the current pulse required for switching, can be seen as it enters the waveguide junction, encircles the center leg of the latching element and emerges at the same point from which it entered. Extreme care was necessary in maintaining the wire in a plane parallel to the RF H-plane so as to minimize the possibility of RF magnetic coupling.

To initially activate the switch, it is necessary to apply a specified current pulse at the ends of the charging wire. Depending upon the polarity of the pulse, the switch is placed in a "latched" condition and the incoming RF energy is directed to either of the two output ports. Reversal of the sense of magnetization by changing the polarity of the switching pulse, results in reversing the direction of circulation. Since the magnetization in toroidal configurations can be reversed rapidly, the resultant device lends itself very well to fast-switching applications.

The fabrication of the ferrite latching element was performed using conventional grinding and ultrasonic cutting techniques. However, the rather strict tolerances inherently characteristic of millimeter wave devices necessitated extreme care. It was observed that a 0.005-inch variation in any direction (i.e., length, width, or thickness) of the ferrite element resulted in shifting the optimum operating frequency approximately 1 GHz.

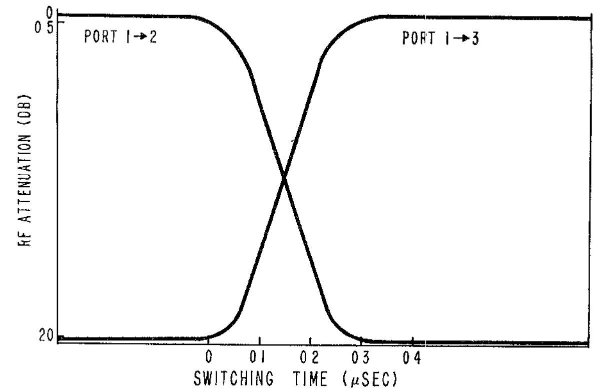

Fig. 5. Switching time.

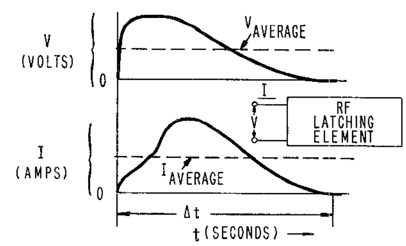

Fig. 6. Typical voltage and current waveforms observed during fast switching of the ferrite element.

Operating Characteristics

Operating characteristics of the device at room temperature are shown in Fig. 7, where it can be seen that the insertion loss has been kept to 0.50 dB maximum, while isolation in excess of 15.0 dB has been maintained. Fig. 8 displays the performance of the device at −60°C, while Fig. 9 shows the operating characteristics at +100°C.

To assure detection of any "spikes" which may be present, all microwave performance data were recorded on swept frequency test systems using permanent record recorders.

Techniques similar to those described in this paper have been used to develop a single-junction four-port latching circulator operating in X-band and three-port devices in both waveguide and stripline at S-, C-, and X-bands.

Final matching of the device was accomplished through the use of external reactive elements, combined with the junction perturbation provided by the Styrofoam spacers, as mentioned earlier.[1]

Switching Characteristics

Switching data are presented in Fig. 5, where it can be seen that switching times of less than 0.30 μs have been achieved, at a specified switching rate of 1 KHz. The switching time is defined as the time required for the isolation of the off port to reach a value of 15.0 dB.

[1] The reader is referred to the following paper which may be used as an excellent guide on matching Y-junction circualtors. J. W. Simon [10].

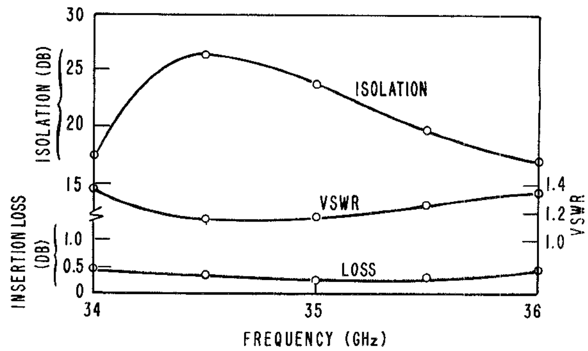

Fig. 7. Operating characteristics at room temperature (26°C).

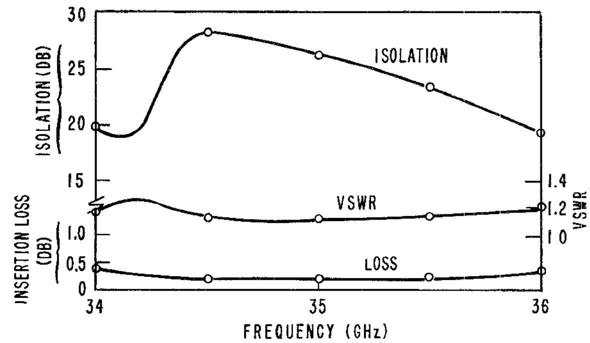

Fig. 8. Operating characteristics at −60°C.

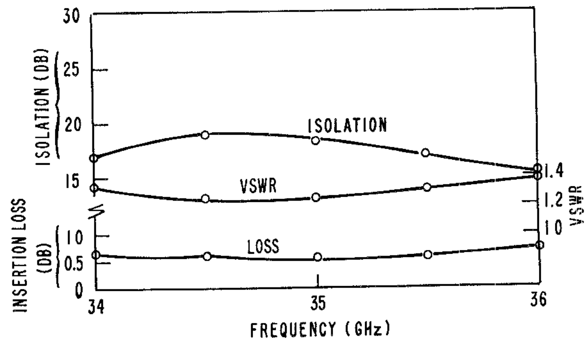

Fig. 9. Operating characteristics at +100°C.

Switching Energy

For this device, the switching energy (u_s) is defined as the amount of energy required to switch the unit from one state of operation to the other. The method used to determine the switching energy is outlined as follows.

The solid traces shown in Fig. 6 depict the voltage pulse across and the current pulse through the charging wire of the RF latching element. These traces are typical of oscillograms obtained using fast-responding voltage and current probes. The switching energy then may be calculated from the following equation [8].

$$\mu_s = V_{av.} I_{av.} (\Delta t) \text{(joules)}$$

where

$V_{av.}$ = average voltage (volts)
$I_{av.}$ = average current (amps)
(Δt) = pulse duration (seconds).

For this device the following data were recorded:

$V_{av.} = 4.2$ volts
$I_{av.} = 2.1$ amps
$\Delta t = 2.0\ \mu s.$

Therefore,

$\mu_s = 17.6\ \mu J.$

In accordance with the above criteria, the switching energy (u_s) associated with this device appears to be in the vicinity of 17.6 μJ.

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Circularly-Polarized Phase Shifter for Use in Phased Array Antennas

M. C. MOHR, MEMBER, IEEE, AND S. MONAGHAN, MEMBER, IEEE

Abstract—An X-band, circularly-polarized, nonreciprocal, ferrite phase shifter has been developed whose size and electrical performance are favorably suited for use in transmission or reflection-type phased arrays requiring element center-to-center spacings of about 0.5 λ. The phase shifter has the same configuration as a Faraday rotator with a ferrite rod located at the center of a circular waveguide with an axially applied field. If a circularly polarized wave is passed through this geometry, a nonreciprocal phase-current characteristic is obtained. The array antenna is configured so that no phase-control field reversals are needed between transmit and receive modes of radar operation. The radiating element has been designed as an integral part of the beam steering element using waveguide array simulator techniques.

This paper will discuss various design problems and performance of the beam steering element. A 1300-element phased array was constructed and tested. Its performance, as it relates to the phase-setting accuracy of 1300 phase-shifter constituents, is stated briefly.

I. Introduction

A MAJOR FACTOR which makes microwave phased-array antenna systems practical today is the advent of phase shifters that are suited for use as beam-steering elements. This array element requires a phaser whose cross-section size is small and its phase easily controllable. The insertion phase and controlled phase characteristic of the device must be reproducible, and because of the large quantities involved, its manufacturing-per-element-cost must be low. In addition, it must have the performance to satisfy the demands of the agile beam-antenna system application.

At microwave frequencies two general types of phase shifters are available for use as beam steering elements—diode phasers and ferrite phasers. The choice depends on the array application in mind; however, the dominating influences in the selection are the per-element specifications of operating frequency, RF power handling and switching speed. Clearly, the best choice of a phase shifter for use in a phased-array application cannot be made without a system tradeoff considering all components between the beam-steering computer input and phase-shifter output.

II. Description of Phase Shifter

The circularly-polarized (CP) ferrite phase shifter discussed in the following is a favorable technical approach for use as a beam-steering element in many array applications. Figure 1 is a cutaway view of the element cartridge showing its various functional components. Figure 2 is a photograph of the same cartridge. An array

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The authors are with the Raytheon Company, Missile Systems Division, Bedford Laboratories, Bedford, Mass.