rated halves of the region can be arranged as in Fig. 9(b) without disturbing the field or the capacitance. Finally, Babinet's transformation is applied to Fig. 9(b), causing all electric and magnetic walls and E and H fields to be interchanged. Thus the E field pattern in (b) is equivalent to the H field pattern in (c). By reversing the direction of the H field lines in the lower half of (c), the magnetic walls on each side of the electric-wall strip may be removed. By Babinet's principle, capacitance per unit length $C_0 = C_{gap}$ in (b) is related to inductance per unit length L_0 in (c) by $C_0/\epsilon = L_0/\mu$. Then since

$$L_0 = Z_0/c,$$

where c is the velocity of light and Z_0 is the characteristic impedance of the cross section in Fig. 9(c), we may write

$$C_{gap} = \frac{Z_0}{377^2 c}.$$

However, if the dielectric sheet has a relative dielectric constant ϵ_{rs}, this should be rewritten as

$$C_{gap} = \frac{\epsilon_{rs} Z_0}{377^2 c} = \frac{\epsilon_0 \epsilon_{rs} Z_0}{377}$$

where Z_0 and c are evaluated for $\epsilon_r = 1$.

High-Power Ferrite Load Isolators

ALVIN CLAVIN†

Summary—The principles of ferromagnetic resonance have been well described in literature. It is the purpose of this paper to point out the application of these principles to the design of practical microwave components, especially for high power. The various types of ferrite microwave circuits that can be used in the design of a load isolator are presented. The advantages and disadvantages of each of these circuits are discussed in regard to the electrical, mechanical, thermal, and magnetic field requirements. Experimental data are given for the optimum design of nonreciprocal ferrite absorbers for rectangular guide. Finally, practical design information for a power circulator in rectangular waveguide is presented which has been modified for use as a load isolator. This device has extremely high isolations (50 db) and low insertion loss (.5 db), and has maintained an isolation in excess of 30 db over a 25 per cent bandwidth with a permanent magnet field. Power handling ability of 250 kw peak with a .001 duty cycle is easily accomplished without external cooling. This isolator requires quite small magnetic fields for proper operations and hence packaged isolator is quite lightweight. Use of this power circulator for high-power modulators and duplexers is discussed.

Introduction

THE principles of ferromagnetic resonance at microwave frequencies have been presented by a number of authors.[1-5] It is not the purpose of this paper to elaborate on their work, but instead to discuss the application of the theory to the design of practical microwave components. According to the theory, if an H field is circularly polarized in a plane perpendicular to the magnetization of a ferrite rod or slab, an increasing phase shift and absorption of power occurs as the value of the magnetizing field is made higher. There is a particular value of the magnetizing field which brings the ferrite into gyromagnetic resonance whenever the sense of the circular polarization is positive (the same rotational sense as the coil current producing the magnetizing field). At this point, a large amount of power is absorbed from the rf field by the ferrite; however, little is absorbed from a wave having negative sense of circular polarization. A plot of the phase shift and power absorption is shown in Fig. 1 as a function of the field

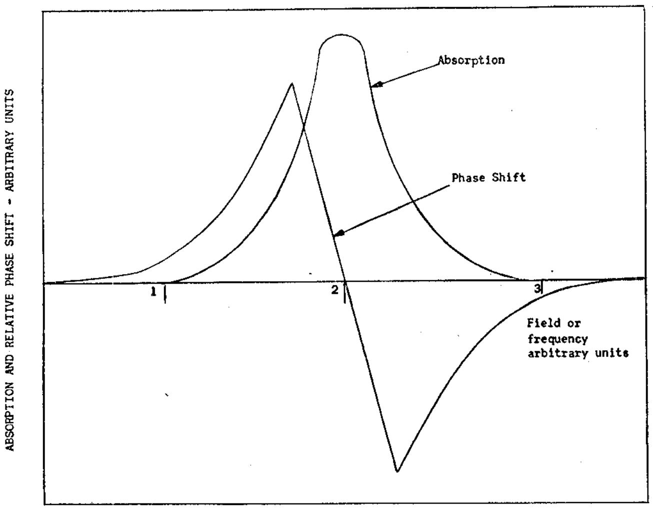

Fig. 1—Relative absorption and phase shift of positively-polarized wave with respect to the negatively-polarized wave.

strength or rf frequency. This is a typical resonant dispersion curve and it should be noted that it is possible to obtain phase shift with very little power absorption

† Canoga Corp., Van Nuys, Calif.

[1] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications," The Microwave Gyrator, *Bell Sys. Tech. Jour.*, vol. 31, pp. 1–31; January, 1952.

[2] J. H. Rowen, "Ferrites in microwave applications," *Bell Sys. Tech. Jour.*, vol. 32, pp. 1333–1369; November, 1953.

[3] H. N. Chait, "Non-reciprocal microwave components," Convention Record of the IRE 1954, part 8.

[4] H. Suhl and L. R. Walker, "Topics in guided-wave propagation through gyromagnetic media, Part I—The completely filled cylindrical guide," *Bell Sys. Tech. Jour.*, vol. 33, May, 1954.

[5] H. Suhl and L. R. Walker, "Topics in guided-wave propagation through gyromagnetic media, Part II—Transverse magnetization and non-reciprocal helix," *Bell Sys. Tech. Jour.*, vol. 33, July, 1954.

by working at the field strengths indicated as 1 or 3 in Fig. 1. Region 2 is, of course, the region of resonant field strength. For nonreciprocal phase shift applications it is desirable to operate at region 1 for X band; however, at lower frequencies, such as S or L band, the absorption peak is closer to the zero axis but it is still possible to operate at region 3.

The nonreciprocal behavior of magnetized ferrite materials has permitted production of a variety of nonreciprocal microwave components. Among the more important of these components is the "load isolator." Its importance is derived from the fact that high power magnetrons become unstable in frequency and power output when subjected to high load vswr's. This deterioration of magnetron performance complicates the radar system considerably. To maintain the vswr of a complex radar system below 1.3 over a large frequency range is quite difficult and expensive. Even very low vswr values may be detrimental to magnetron performance when the magnetron is connected to the source of reflections by a long transmission line.[6]

The load isolator corrects this problem by either diverting the reflected energy into a dummy load or absorbing it in the ferrites so that it cannot reach the magnetron. There are a number of different microwave circuits that can be used to accomplish this isolation. Each has certain advantages and disadvantages which will be discussed in detail in the following sections.

Circular Waveguide Ferrite Components

Polarization Rotator

A TE_{11} mode wave in a circular waveguide can be considered as the sum of two circularly polarized waves of opposite sense. If the wave were allowed to pass through a small cylinder of ferrite suspended in the guide with an applied longitudinal magnetic field, a change in propagation would take place for the positive wave and little change would occur in the negative wave. If the dc field were adjusted to operate in the region 1 of Fig. 1, then there would be a relative phase shift of the positive wave with respect to the negative wave and little attenuation would result. As a result of this relative phase shift, the wave experiences a rotation of polarization in passing through the ferrite section. Reflected waves from the antenna in passing back through the ferrite are again rotated in the same direction (nonreciprocal rotation). If the original rotation were 45°, then the reflected wave would be orientated at 90° with respect to the input polarization and could be coupled out into a dummy load without affecting the input wave.

There are two configurations that could be employed in the design of such an isolator. The first design would locate the magnets internally, that is, adjacent to the ferrite. This makes possible the use of small magnets and results in an over-all reduction in weight. However, this design is quite narrow band due to multiple reflections between the ferrites and the magnets. In the second design the magnets are placed external to the waveguide. This procedure improves the bandwidth, however, due to the increased air gap, the magnets are larger and heavier.

This isolator is operated in the low absorption region of the resonance curve and can be designed with small insertion losses. However, this type of design is considered good only for low or moderate power applications. This is due to the poor thermal circuit for dissipating the heat in the ferrite caused by the insertion loss. Forced convection must be used to cool the ferrite for high power use and in the case of a pressurized waveguide system this is a costly and difficult task.

A design in which the ferrite is in direct contact with the waveguide wall would produce considerably greater cooling. Designs which take advantage of this feature can be made in rectangular waveguide.

Rectangular Waveguide Ferrite Components

Differential Absorber

It is easily shown that in rectangular waveguide the magnetic vector is circularly polarized in the transverse plane at a point between the guide centerline and the guide edge.[7,8] It is only necessary, therefore, to place a ferrite strip at this point and apply the correct field. By operation at the low loss region of the dispersion curve nonreciprocal differential phase shift can be obtained. Isolators can be built that operate at this point and are discussed later. Operation at point 2 in Fig. 1 produces nonreciprocal absorption of power and it is this type of device that is to be discussed in this section. It has been found that strips placed completely across guide, as in Fig. 2(a) (next page), yield poor front to back power absorption ratios unless the strip is impractically thin. However, the configuration of Fig. 2(b) gives quite excellent front to back ratios. The field requirement in the configuration of Fig. 2(b) is considerably higher and large magnets must be used. Also, the insertion loss will be higher than that of the polarization rotator. Disadvantages mentioned are somewhat offset by simplicity of construction and lower costs.

A number of different geometries of ferrite strips were measured to see if there existed an optimum ratio of width t to height h. These data are shown in Fig. 3 (next page). It should be noticed that for every width of ferrite strip there is a height which gives the maximum isolation to loss ratio. It is also apparent that there is an optimum width which gives the best possible ratio. The information obtained is for standard X band $1\times\frac{1}{2}$

[6] J. F. Hull, G. Novick, and R. Cordray, "How lone-line effects impairs tunable radar," *Electronics*, vol. 27, pp. 168–173; February, 1954.

[7] Chait, *op. cit.*

[8] B. Lux, K. J. Button, and L. M. Roth, "Ferrite phase shifters in rectangular waveguide," *Jour. App. Phys.*, vol. 25, no. 11, pp. 1413–1423; November, 1954.

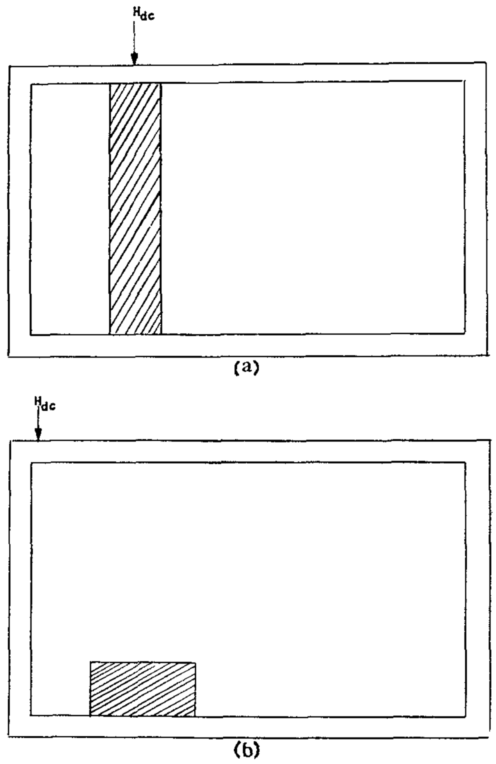

Fig. 2(a) Ferrite across guide; (b) Ferrite partially across guide.

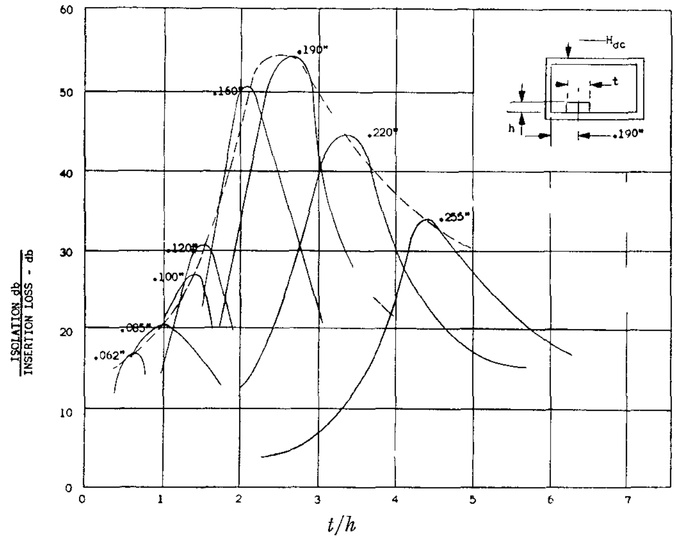

Fig. 3—Ratio of isolation to insertion loss for ferroxcube 106 as a function of width to height for various widths at 9,000 mc.

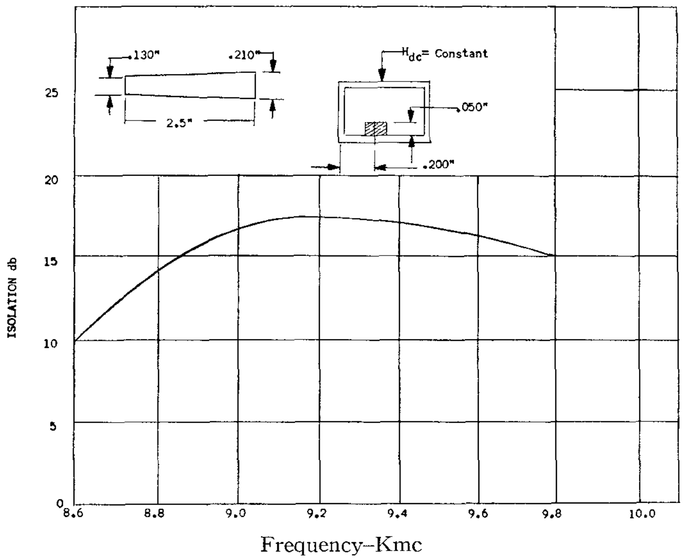

Fig. 4—Isolation as function of frequency for a tapered ferrite strip operating as a differential absorber.

waveguide and care should be used in extrapolating the data to other waveguide sizes and frequencies.

In the course of these investigations on geometry it was found that the magnetic field required to produce resonance was greater for wider strips of the same height than for narrow strips. Since the field required for resonance is less at lower frequencies than for higher frequencies, it was thought possible to compensate the loss of isolation with frequency by tapering the ferrite strip. The results of this experiment are shown in Fig. 4. The height of the tapered strip shown is less than the optimum indicated by Fig. 3. However, the increase in bandwidth (frequencies where isolation drops 3 db) over a nontapered section was 2 per cent.

In the above described experiments Ferroxcube 106 material was used. This material was chosen because the Curie temperature is greater than 500°C. With this material it is possible to dissipate 45 w of average power in the ferrites without losing isolation. This has been accomplished without forced air cooling.

This type of isolator has a number of advantages. The thermal circuit for dissipating heat is excellent, and the construction is extremely simple. However, there are also disadvantages such as the requirement for a large heavy magnet to produce resonance. Since all reflected power is absorbed in the ferrite, the power handling ability is limited by the vswr of the load. The insertion loss of the differential absorbers is in general higher than that of the rotator or the differential phase shift type to be described in the next section. For this latter type of isolator, ratios of isolation in db to loss in db in excess of 100 have been obtained while ratios of 50 are about the maximum that can be obtained from differential absorbers. Generally speaking, a low value of insertion loss, which is necessary for high power application, can be accomplished only with a sacrifice of isolation.

Differential Phase Shift Isolator

A series of measurements have been presented concerning nonreciprocal phase shift, and the microwave circuits necessary to make circulators.[9] The meaning of the term "circulator" can be understood from Fig. 5(a).

[9] Chait, *op. cit.*

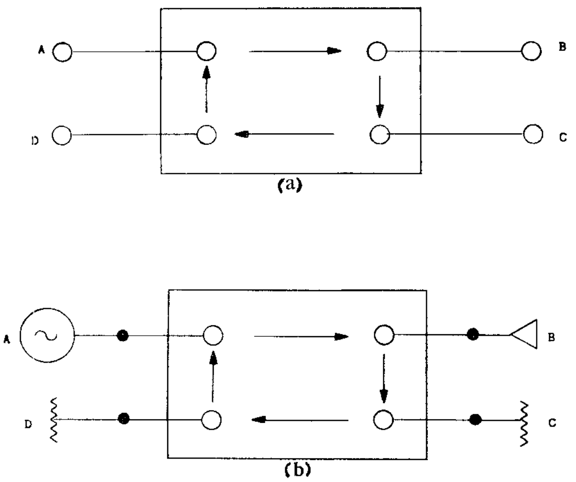

Fig. 5(a) A schematic representation of a circulator; (b) Modification of circulator to produce a load isolator involving two dummy terminations.

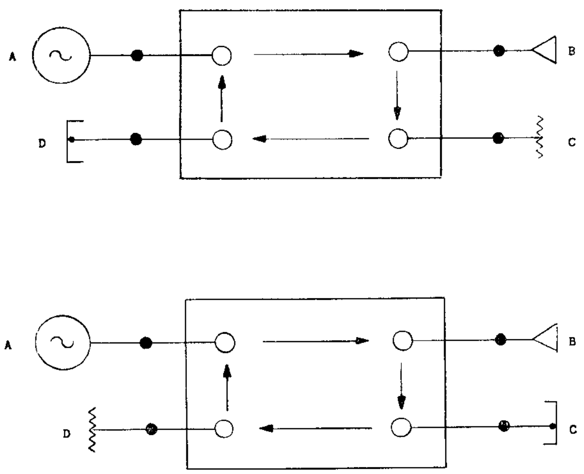

Fig. 6—Modification of circulator to produce a load isolator in which only one dummy termination and a short circuit are used.

Consider a box from which emerge four waveguide ports. If power were incident at port A it would leave at port B. The reciprocal situation would imply that power incident at B would return to A; however, in a circulator which is nonreciprocal, it emerges from C. Power incident at C leaves at D and power incident at D leaves at A. The circulator circuit can be modified to produce a large number of components, such as load isolators, modulators, power dividers, and duplexers. For example, consider the modification shown in Fig. 5(b). Power incident at terminal A leaves at B. Reflected power from the antenna at B goes to C where it is absorbed in a load. If the load at C is not perfectly matched the reflected power goes to D where it is absorbed. This load isolator involves two dummy loads. A simplification can be made as shown in Fig. 6.

In these circuits one of the dissipating loads is replaced by a short circuit. Practically speaking, there is little preference regarding either of these two circuits

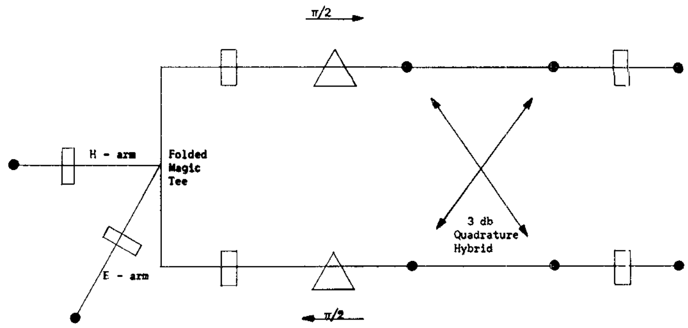

Fig. 7—Microwave circuit for differential phase shift load isolator.

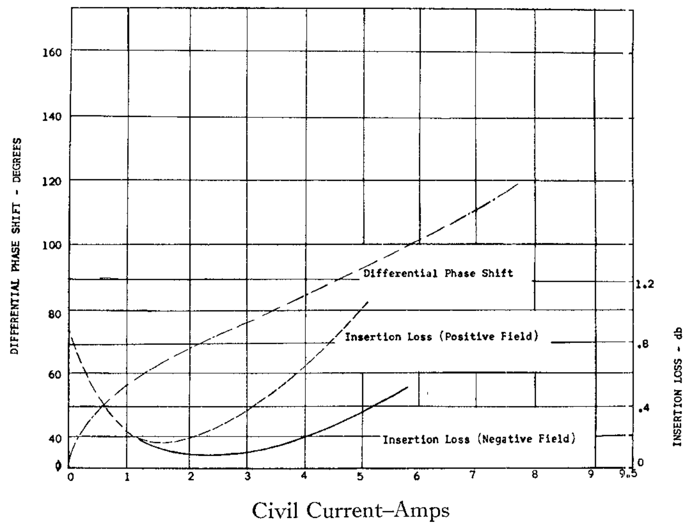

Fig. 8—Differential phase shift and insertion loss as a function of coil current for a ferrite strip 1.4″×.4″×.050″, f=9,000 ma.

from a performance point of view. Obviously, reflections from the dummy loads are now not second order effects and can affect the isolation considerably. It is quite important, therefore, that these loads be well matched.

The microwave circuit used to make the circulator to be discussed is shown in Fig. 7. In this circuit only one-half of the power need be handled by each ferrite section. Also the insertion loss of one section balances that of the other so as to obtain better isolation. The problem of designing the ferrite phase shift sections for this circulator are of interest. It is necessary, of course, to obtain the desired phase shift over a broadband of frequencies and to maintain the minimum insertion loss possible. It is also important that each phase shift section be matched to the waveguide over a broadband of frequencies. It was decided that if the strip was thin the incident wave would be least disturbed, resulting in broader band performance. A .050 strip was chosen for the experiments. In Fig. 8 is shown a curve of differential phase shift and insertion loss as a function of coil current for a strip .050 wide and 1.4 inches long. Notice that the insertion loss is minimum just beyond the saturation point for the ferrite. The differential phase shift

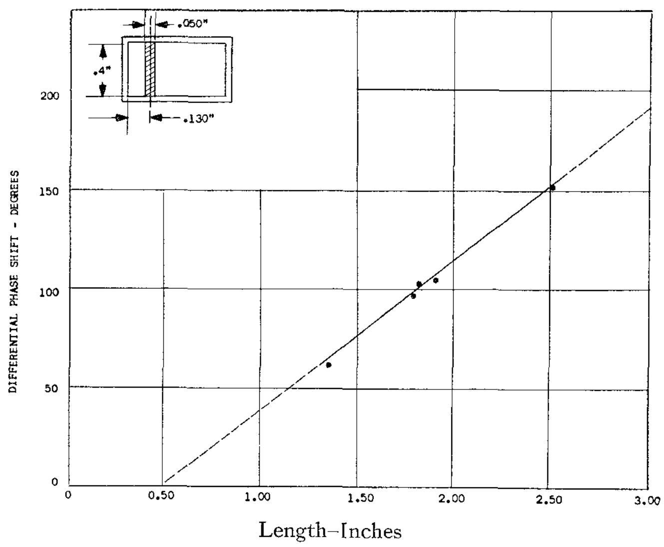

Fig. 9—Differential phase shift at minimum insertion loss as a function of ferrite length.

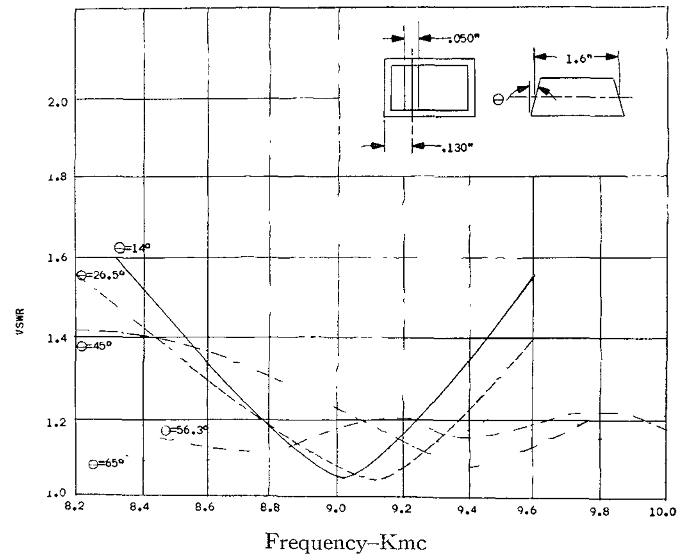

Fig. 11—VSWR vs frequency for various taper angles on the leading edge of the ferrite. Field constant is at minimum loss value.

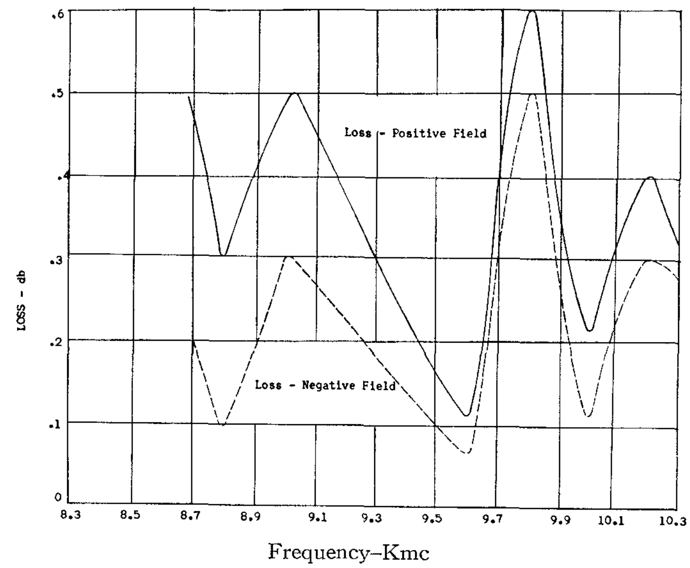

Fig. 10—Insertion loss vs frequency for a ferrite strip 1.4″×.4″×.050″, magnetic field constant 2 amps.

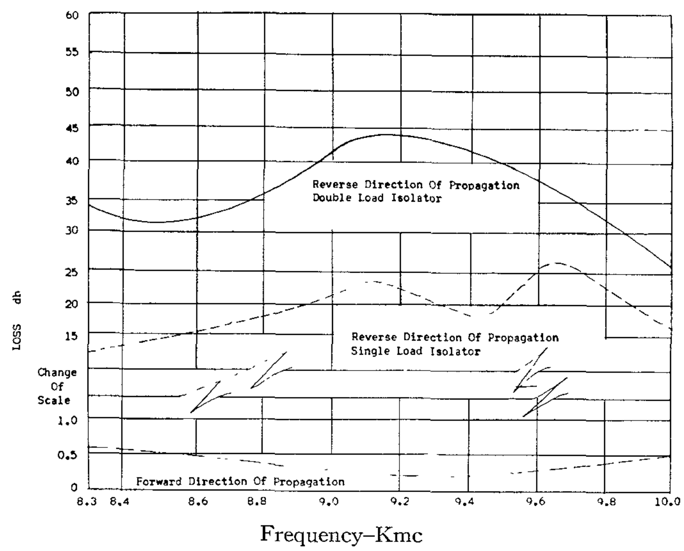

Fig. 12—Loss vs frequency for both forward and backward directions of propagation, single and double load differential phase shift ferrite load isolator.

is very constant with frequency beyond the saturation point. However, if the current is increased to a point where the ferrite begins to absorb power due to the resonance phenomena the phase shift is not constant with frequency. The field point where the insertion loss is smallest is also the most broad band point of operation. In Fig. 9 is shown a curve of phase shift as a function of the strip length, at the point of minimum insertion loss. The insertion loss is not as constant with frequency as is the differential phase shift. The variation of insertion loss with frequency for the strip of Fig. 8 is shown in Fig. 10. Note that the loss is not quite the same for the two directions of propagation.

An additional problem is that of matching the ferrite strips. To accomplish this, experiments were performed with different taper lengths on the leading edge of the ferrite sections. In Fig. 11 is shown the frequency vs vswr characteristics of these strips as a function of the taper angle.

From this design information an optimum strip was selected and used to build the circulator of Fig. 7. The performance of this device as a single load isolator and a double load isolator is shown in Fig. 12.

The input vswr over the same band is less than 1.25.

It is apparent that the electrical performance of this isolator is superior to those of other types. The weight is considerably less while the power handling ability is very high, since there is cooling available by the waveguide walls. The isolator has long length since it employs two hybrid junctions and this presents an installation problem in existing equipment; however, new equipments should find these isolators quite attractive.

Circulator can easily be used as a ferrite duplexer by replacing short circuit at terminal *c* of Fig. 6 by a TR tube and mixer. Operation is as follows: Power from magnetron enters the circulator at A and leaves at B. Reflections from an imperfect load at B enter C and are reflected by the fired TR tube to the load at D. Signal from the target enters B at a later time when the TR tube is not fired and goes to the signal mixer and receiver. In this method of operation the isolation is equivalent to that of a single load isolator; however, one can obtain performance equivalent to that of a double load isolator by incorporating an additional isolator in front of the TR tube. This additional isolator will cause the TR tube to appear as a matched load and the performance will therefore be equivalent to that of a two load isolator.

A comparison of the losses (see Table I) involved in a circulator when used as an isolator-duplexer and those involved with a dual TR—quadrature hybrid duplexer are shown below. In this analysis it is assumed that a load isolator is an absolute requirement for a high power tunable radar system.

TABLE I

Circulator		Dual T.R. Duplexer	
A. Transmit 1. Circulator	0.5	1. Load isolator	0.5
(T.R. tube decoupled—no arc loss present)		2. T.R. arc loss	0.6
B. Receive 1. Circulator	0.5	1. Dual T.R. tube insertion loss	0.6
2. Single T.R. insertion loss	0.5		
Total	1.5 db		1.7 db

The two-way losses involved within these two duplexers are comparable; however, there is considerable space savings possible with a circulator. Also note that there is more power available at the antenna with a circulator, and this improves the signal to target noise ratio.

A photo of a prototype circulator is shown in Fig. 13.

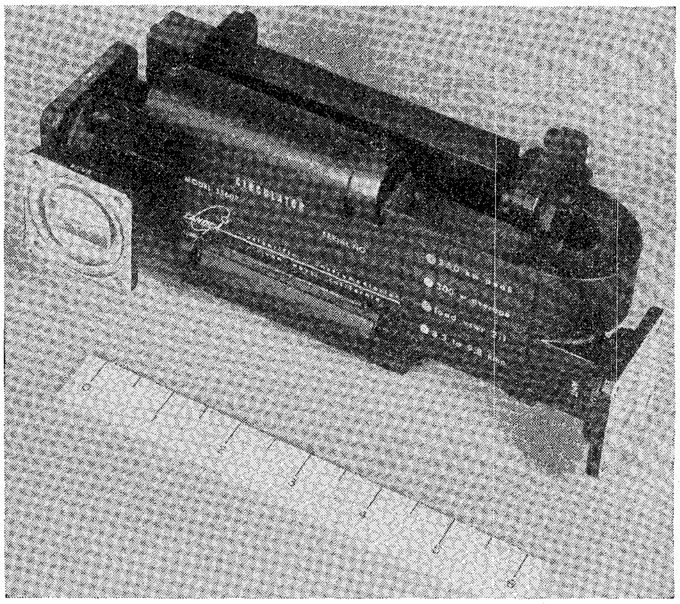

Fig. 13—Prototype circulator.

By using electro magnets instead of permanent magnets one can build a power divider or audio modulator. The advantage of this type of design for a modulator is that the audio driving power is quite low since the magnetic field requirement for phase shift is very low.

Conclusions

Polarization rotators have cooling problems when used as high power isolators because of the poor thermal conducting circuit.

Differential absorbers can handle quite high powers without cooling; however, their insertion loss is high and isolation low. Also, they require heavy magnets. These disadvantages are offset by their simplicity of construction.

The differential phase shift circulator in rectangular waveguide has high isolation, low insertion loss, light weight, and high power handling capabilities. However, it is longer and more costly to build than the differential absorbers.