Design of a Full Waveguide Bandwidth High-Power Isolator*

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Summary—An analysis of the microwave fields in rectangular waveguide indicates that circular polarization of the *H*-vector components exists at two planes only and the location of these planes is frequency dependent. Also, an examination of Kittel's theory reveals that resonance in ferrites can be made to occur at different frequencies for a constant value of dc magnetic biasing field provided the ferrites are characterized by different values of saturation magnetization. These two effects have been used concurrently in the design of an *X*-band waveguide isolator for operation over a 45 per cent bandwidth, and at high power levels. The theory underlying the design of this isolator is presented. Included is a treatment of the parameters which affect the isolator design. Finally, an operative isolator is described and its experimental characteristics are reported.

INTRODUCTION

IN recent years considerable emphasis has been given to the development of ferrite isolators for microwave applications.[1-6] Isolators have been designed and built for use in low-power narrow band, low-power broadband, and high-power moderate bandwidth applications. However, a description of an isolator designed both for high-power and extremely broad-band application has not yet appeared in the literature. It is the purpose of this paper to describe an isolator of the latter type which operates at gyromagnetic resonance.

In the isolator to be described in this paper, broadbanding is achieved by utilizing ferrites of different saturation magnetization in a constant magnetic biasing field. Each ferrite exhibits a different gyromagnetic resonant frequency and the ferrites are selected in a manner so as to distribute resonance frequencies throughout the required bandwidth of the isolator. Furthermore, each ferrite is located at a position such that it is in a plane of microwave *H*-vector circular polarization at its resonant frequency, and in a region of elliptical polarization at frequencies away from resonance. In this manner, each ferrite exhibits differential attenuation at its resonant frequency and contributes practically no forward (negative) wave magnetic loss at other frequencies. It will be shown that a combination of ferrites operating under these conditions, and in the presence of a single dc magnetic biasing field, will exhibit a large nonreciprocal attenuation over a very broad frequency range while maintaining a very low-forward-wave loss.

The manner in which ferrite location and saturation magnetization affect nonreciprocity over a wide frequency range is treated. Design considerations for the development of a very broad-band *X*-band rectangular-waveguide isolator are presented. Finally an operative high-power 45 per cent bandwidth *X*-band isolator is described and data are presented on its attenuation and VSWR characteristics.

DESIGN CONSIDERATIONS

The position of *H*-vector circular polarization in rectangular waveguide depends upon the dimensions of the waveguide, operating frequency, and mode of operation. Circular polarization of the microwave *H*-vector components (H_x and H_z), as given by Moreno,[7] have been shown to exist in two planes (henceforth referred to as CP planes) for propagation in the dominant TE_{10} mode.[1] The location of the two CP planes with respect to the narrow waveguide walls is given by

$$\frac{x}{a} = \frac{1}{\pi} \tan^{-1} \left[\left(\frac{\nu}{\nu_c} \right)^2 - 1 \right]^{-1/2} \tag{1}$$

where

x = distance from the narrow waveguide wall,
a = broad dimension of waveguide,
ν_c = cutoff frequency of waveguide,
ν = operating frequency.

It follows from (1) that the planes of circular polarization are located equidistant from—and parallel to—the narrow walls of the waveguide. Also these planes are infinitely thin and their location is frequency dependent. The manner in which the location of the CP planes shift

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[1] A. G. Fox, S. E. Miller, and M. T. Weiss, "Behavior and application of ferrites in the microwave region," *Bell Sys. Tech. J.*, vol. 34, pp. 65–103; January, 1955.

[2] S. Weisbaum and H. Boyet, "A double-slab ferrite field displacement isolator at 11 kmc," PROC. IRE, vol. 44, pp. 554–556; April, 1956.

[3] A. Clavin, "High-power ferrite load isolators," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-3, pp. 38–44; October, 1955.

[4] P. H. Vartanian, J. L. Melchor, and W. P. Ayres, "Broadbanding ferrite microwave isolators," 1956 IRE CONVENTION RECORD, pt. 5, pp. 79–83.

[5] P. H. Vartanian, J. L. Melchor, and W. P. Ayres, "Broadband ferrite microwave isolator," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 8–13; January, 1956.

[6] M. L. Kales, H. N. Chait and N. G. Sakiotis, "Non-reciprocal microwave component," *J. Appl. Phys.*, vol. 24, pp. 816–817; June, 1953.

[7] T. Moreno, "Microwave Transmission Design Data," McGraw-Hill Book Co., Inc., New York, N. Y., p. 115; 1948.

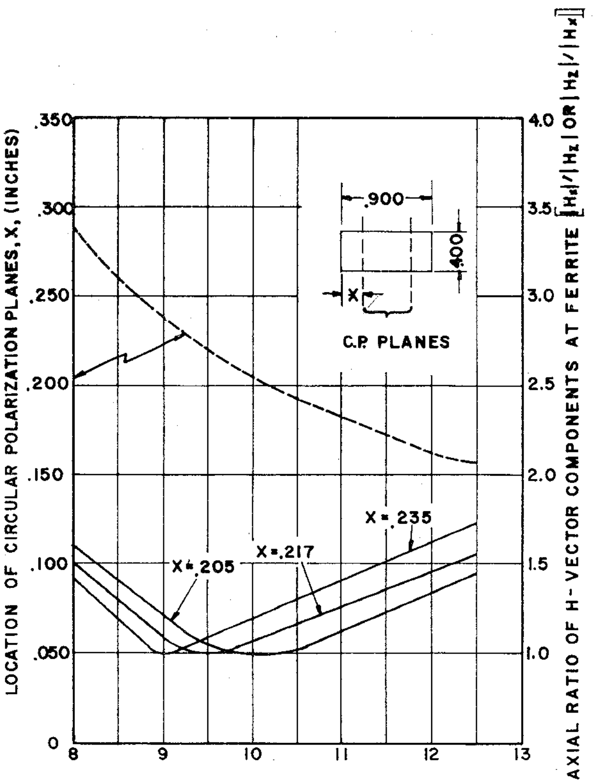

Fig. 1—Frequency dependence of the microwave H-vector CP planes in rectangular waveguide. Also shown is the frequency dependence of axial ratio at various points in the waveguide.

with frequency is depicted in Fig. 1. The CP planes shift toward the center of the waveguide as cutoff is approached and toward the waveguide narrow walls as frequency is increased It follows that for a given position in the waveguide, true microwave H-vector circular polarization will exist at a single frequency only and that at any other frequency an elliptical polarization exists.[1] The degree of ellipticity of the polarization, *i.e.*, the axial ratio of the wave can be obtained as follows

$$AR = \frac{|H_x|}{|H_z|} = \left[\left(\frac{\nu}{\nu_c}\right)^2 - 1\right]^{1/2} \tan\frac{\pi x}{a}\cdot \qquad (2)$$

The microwave H-vector axial ratio, *i.e.*,

$$\frac{|H_x|}{|H_z|} \quad \text{or} \quad \frac{|H_z|}{|H_x|}$$

as a function of waveguide position is also shown in Fig. 1 with frequency as a parameter.

In rectangular waveguide the dc magnetic biasing field must of course be oriented perpendicular to the broad waveguide walls in order to obtain optimum nonreciprocal effects in ferrites located in the CP planes. The direction of the applied magnetic field must also be compatible with the direction of propagation to give the desired nonreciprocal effects.

The equation describing gyromagnetic resonance in ferrites shows that for a constant applied dc magnetic field, resonance can occur at only one frequency. Gyromagnetic resonance for a slab of ferrite whose thickness is small compared to a wavelength in the medium can be approximately described by[8]

$$\nu_r = \gamma[H_a - 4\pi M_s] \qquad (3)$$

where $\gamma = 2.8$ mc/oersted (the gyromagnetic ratio of an electron), H_a = external dc magnetic field required for resonance, and $4\pi M_s$ = saturation magnetization of the ferrite.

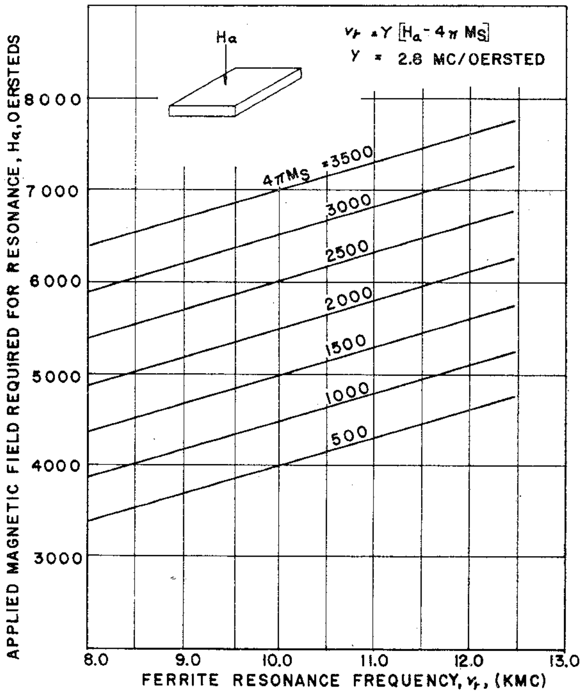

Fig. 2—Frequency dependence of resonance field for ferrites of various $4\pi M_s$.

The dependence of resonance field on frequency as determined using (3) is given in Fig. 2 for various values of $4\pi M_s$. It is evident from the figure that ferrite resonance can be obtained over the full RG-52/U waveguide bandwidth (8.2 to 12.4 kmc) for a constant applied magnetic field by using ferrites with different values of $4\pi M_s$.

EXPERIMENTAL CHARACTERISTICS

Using the results derived in the previous section of this paper a broad-band high-power ferrite isolator was designed for operation at X-band frequencies. A photograph of the isolator is given in Fig. 3, and its configuration and attenuation characteristics plus VSWR data are given in Fig. 4. Four thin ferrite slabs used in this isolator (Fig. 4) are located flat against the broad walls of rectangular waveguide and each is located in the plane of CP at approximately its resonance frequency. In the isolator design of Fig. 4 the two high $4\pi M_s$ ferrites are located end to end against the top waveguide broadwall whereas the two low $4\pi M_s$ ferrites are similarly located against the bottom waveguide broadwall.

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[8] C. Kittel, "On the theory of ferromagnetic resonance absorption," *Phys. Rev.*, vol. 73, pp. 155–161; January 15, 1948.

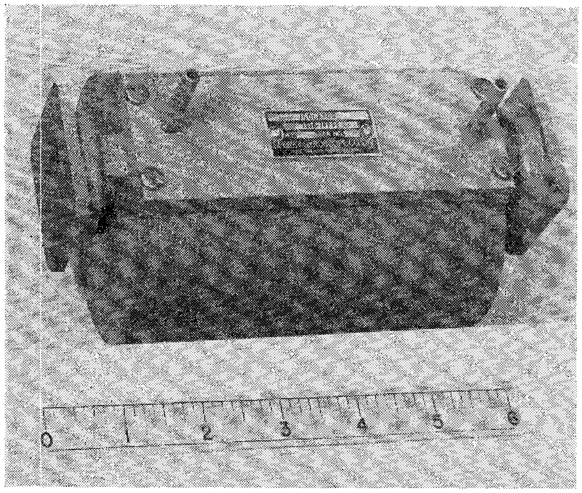

Fig. 3—Assembled version of the X-band isolator.

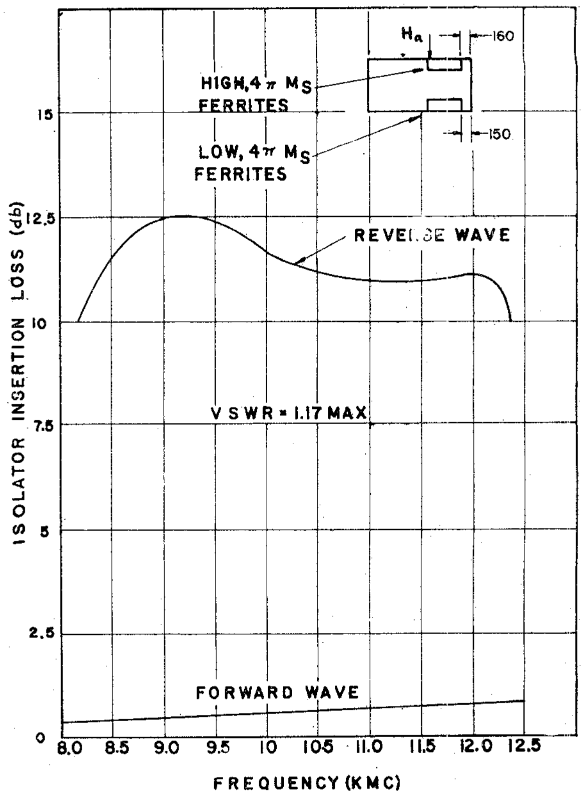

Fig. 4—Physical configuration and attenuation characteristics of the X-band isolator.

When located as above in rectangular waveguide, this ferrite configuration offers the advantages over other ferrite shapes of permitting operation at higher peak-power levels without encountering breakdown, and of operating into larger load mismatches without excessive ferrite heating. Also, it can be shown that within the range of values of ferrite saturation magnetization presently available, one of the largest operating bandwidths attainable in high-power rectangular waveguide isolators can be obtained using the isolator configuration depicted in Figs. 3 and 4. Finally, for this configuration the input VSWR can be maintained at a smaller value, and the reverse to forward wave attenuation ratio at a larger value, over the bandwidth than with other configurations presently available and adaptable to high-power use. The presence of all of these desirable features in a single unit gives rise to an isolator which will give satisfactory performance under high-power conditions even when operating into large load mismatches.

The saturation magnetization of the four ferrites employed in the broadband isolator are approximately 2000, 2500, 3300, and 3500 gauss. The resonance frequencies of thin ferrite slabs of the materials as given in Fig. 2 for an applied field of 6500 oersteds are 12.5, 11.5, 9.0, and 8.4 kmc, respectively. The listed ferrites are seen to exhibit resonance frequencies distributed over approximately the desired operating band. An even better distribution would require different value $4\pi M_s$ ferrites which were not immediately available.

Now it is well known in the ferrite art that (3) holds only for the case where the ferrite thickness is small compared both to a wavelength in the medium and the broad dimension of the ferrite. Furthermore, any deviation from these conditions will result in an increase in ν_r for a constant H_a or a decrease in H_a at a constant frequency. It follows that by varying the ratio of ferrite width to thickness the resonance frequency of a given ferrite can be adjusted within limits as described by Kittel[8] while still maintaining H_a constant. Hence, the dimensions of the ferrite slab used in the isolator were adjusted until it was determined experimentally that the slabs were resonating at the desired frequencies. This shaping of the ferrite slabs resulted in a small deviation from the conditions set forth by Kittel, and a reduction in the H_a required for isolator operation.

Lax[9] has shown that for the ferrite waveguide configuration described herein the location of the CP planes should correspond to those of empty waveguide, and that CP should exist within the ferrite. It was also observed, however, that the presence of the ferrite in the waveguide resulted in an alteration of the location of the planes of circular polarization at each frequency. This can be attributed to the ferrites used in this case being larger than assumed by Lax in his theoretical treatment of this configuration. From Fig. 1 it is seen that the plane of circular polarization for empty waveguide, or waveguide loaded with very thin slabs, shifts from 0.268 inch at 8.2 kmc to 0.158 inch at 12.4 kmc. It has been found experimentally, however, that when ferrite slabs of a practical thickness are used, the best characteristics are obtained when a much smaller shift is assumed. It was further observed that very desirable attenuation characteristics can be obtained with the center of two of the ferrites located at a distance of 0.230 inch from a narrow waveguide wall and the center of the remaining two at a distance 0.210 inch. The ferrites nearest the narrow waveguide wall are, of course, the two ferrites of

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[9] B. Lax, "Frequency and loss characteristics of microwave ferrite devices," Proc. IRE, vol. 44, pp. 1368–1386; October, 1956.

smallest $4\pi M_s$ while the ones farthest from the narrow wall are the remaining two ferrites.

The relatively small observed shift of the CP planes as compared to the theoretical empty waveguide can probably be interpreted as being due in part to an effective decrease in the waveguide cutoff frequency caused by the presence of the ferrites and, hence, to a decrease in the shift with frequency of the positions of the CP planes. Also, since ferrites are dielectrics, exhibiting high dielectric constants, it follows that under certain conditions as encountered here they may tend to concentrate the microwave field and hence further reduce the shift of the planes of CP. The magnitude of the effects are, of course, dependent upon the quantity of ferrite present in the waveguide. Similar effects have been observed by other workers including Vartanian[5] who placed an additional dielectric other than ferrite into the waveguide.

An additional important feature of this isolator which aids in maintaining an almost constant reverse attenuation over the entire bandwidth is the use of high $4\pi M_s$ ferrites to obtain differential attenuation at the low end of the frequency band and low $4\pi M_s$ ferrites to achieve the same characteristics at the high end of the band. The need for higher $4\pi M_s$ ferrites to maintain the desired reverse-wave attenuation at the low end of the operating band stems from the decrease in resonance attenuation with frequency for a constant $4\pi M_s$ ferrite and the increase in resonance attenuation with ferrite $4\pi M_s$ for a constant frequency.

A photograph of the 8.2 to 12.4-kmc high-power isolator is shown in Fig. 3 and its configuration; low-power attenuation characteristics and maximum VSWR are depicted in Fig. 4. High-power tests have been conducted on this isolator without the use of liquid cooling which indicates that average powers in excess of 250 watts, with peak powers in excess of 250 kw, can be propagated continuously without deterioration of attenuation below approximately 10 db when looking into a load VSWR of 3:1. Higher microwave power levels can be propagated when the isolator is liquid cooled, or the microwave circuit in which the isolator is located is terminated in a better matched load.

While the effect of ferrite resonance linewidth was not treated in this paper it can play an important role in the design of the broad-band isolators. This effect can generally be compensated for by varying the number of different $4\pi M_s$ ferrites used to cover the desired frequency band and their size, provided extremely broad resonance linewidth ferrites are not used. In the present application ferrites characterized by moderate resonance linewidths were used.

CONCLUSIONS

The design of broad-band isolators in rectangular waveguide can be achieved by using ferrites of different or varying $4\pi M_s$, each of which is located in a plane of microwave H-vector circular polarization in rectangular waveguide at its resonance frequency. Under ideal conditions, for a given desired operating bandwidth the values of ferrite $4\pi M_s$ and ferrite waveguide location can be determined with a fair degree of accuracy. In many nonideal conditions the same quantities can be determined to an order of magnitude. By proper selection of ferrite configuration very high-power operation can be effected. Using the information thus derived an extremely broad-band high-power X-band rectangular waveguide isolator was constructed which operates over a 45 per cent bandwidth with a forward-wave attenuation of less than 1.0 db and a reverse-wave attenuation in excess of 10 db.

ACKNOWLEDGMENT

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Correction

Robert E. Collin, author of "A Simple Artificial Anisotropic Dielectric Medium," which appeared on pages 206–209 of the April, 1958 issue of these TRANSACTIONS, wishes to make the following correction to his paper.

Eq. (13) on page 208 is incomplete and it should be replaced by

$$k_0 S < \frac{2}{\sqrt{\kappa}(1+n_x)}.$$