Broad-Band Isolators and Variable Attenuators for Millimeter Wavelengths*

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Summary—**A longitudinally magnetized rod of ferrite has been used as a dielectric waveguide which provides Faraday rotation independent of frequency in the band from 50 to 60 kMc. This rotator has been incorporated into broad-band isolators with forward losses of 1 db and reverse losses greater than 30 db with return losses of approximately 20 db over this band. It has also been used in a variable attenuator with a minimum loss of 1 db and a maximum loss greater than 30 db which is essentially constant over the band.**

Advantages of this type of rotator at millimeter wavelengths include bandwidths in excess of 20 per cent, low field requirements (25–50 oe), relatively large dimensions, the use of common ferrites, and the absence of conducting waveguide walls which permits rapid switching of the control field.

The last feature has been utilized in an automatic power leveling system capable of removing variations of several kc frequency content from the swept output of a millimeter wave BWO.

A BROAD-BAND Faraday rotation isolator and variable attenuator have been developed to operate in the millimeter wave region of 50 to 60 kMc. These devices utilize the rather old but unexploited concept of a dielectric rod waveguide composed entirely of ferrite to give the following typical device characteristics:

Isolator	
Forward loss	< 1 db
Reverse loss	>30 db
Return loss	$\sim$20 db
Field required	$\sim$30 oe.
Variable Attenuator	
Minimum loss	$\sim$ 1 db
Maximum loss	>30 db
Return loss	$\sim$20 db
Field required for maximum loss	$\sim$30 oe.

The bandwidth of these devices exceeds that of any other isolator or attenuator known to the author to operate at these frequencies, while the high, low and return loss values are comparable with other such devices. Notable features of these devices include the use of a common ferrite, a low (25–50 oe) longitudinal field, and the absence of conducting waveguide walls, which makes the field readily switchable.

Device Description

The isolator, which is very similar to the attenuator in appearance, is pictured in Fig. 1. Input and output ports for the devices are rectangular waveguides with the planes of polarization for the dominant modes in the two guides oriented at 0° to one another for the variable attenuator and at 45° to one another for the isolator. The rotator section between the input and output is a dielectric waveguide suspended in a nonconducting cylinder by means of plastic supports and coupled to the rectangular waveguides by simple tapers in the dielectric guide which protrude into the rectangular guides. The attenuator films which provide the reverse loss in the isolator and the variable loss in the attenuator are deposited metal films sandwiched into each end of the dielectric waveguide. Shielding from ambient fields is provided by μ-metal cylinders which encircle the devices over their entire length. The magnetic field is applied by means of an adjustable permanent magnet or a low-inductance solenoid coil as the application demands.

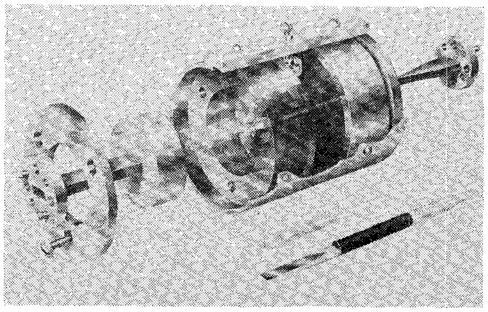

Fig. 1—A broad-band 50 to 60 kMc isolator utilizing a dielectric waveguide rotator.

Figs. 2 and 3 show the performance of typical attenuators and isolators of this type. The dashed curves superimposed on the curves of Fig. 3 indicate, for comparison, the performance of a "conventional" Faraday rotation isolator (built at Bell Telephone Laboratories) utilizing a 0.030-in rod of ferrite in a 0.200-in diameter metallic waveguide. In each case the magnetizing field has been held constant and the losses plotted as functions of frequency. The reverse loss of Faraday rotation isolators is greatly dependent upon the angle of rotation. Thus, the frequency dependence of the angle of rotation for the "conventional" rotator is indicated by the sharp peaking of the reverse loss (dashed curves of Fig. 3). Similar peaking would occur in the maximum loss for a "conventional" Faraday rotation attenuator. Contrast this peaking with the nearly constant, high maximum loss of the dielectric waveguide attenuator (Fig. 2) and

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reverse loss of the dielectric waveguide isolator (solid curves of Fig. 3). Comparing bandwidths on the basis of reverse loss, we see that the "conventional" rotator has a 30 db bandwidth of only 1 kMc while the 30 db bandwidth of the dielectric guide isolator exceeds 10 kMc. Note that the forward losses are comparable for the two isolators so that the reverse loss comparison is truly indicative of their relative bandwidths.

Return loss data was not available for the "conventional" Faraday rotation isolator. The return losses for the dielectric guide devices as indicated in Figs. 2 and 3 fluctuate some, but stay greater than 20 db over much of the band. A discussion of some of the sources and remedies for the remaining mismatch is included in the text.

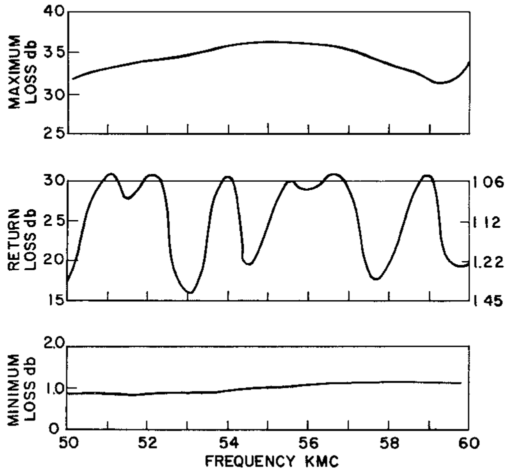

Fig. 2—Typical loss characteristics of a broad-band 50–60 kMc variable attenuator. The minimum loss is obtained with a 0 applied field and the maximum loss with a constant 30 oe applied field.

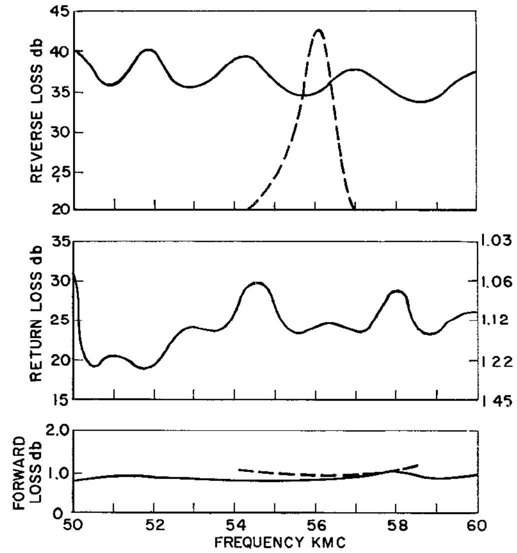

Fig. 3—Typical loss characteristics of a broad-band 50 to 60 kMc isolator (solid curves) with the characteristics of a "conventional" Faraday rotation isolator (dashed curves) for comparison. In each case the applied field was held constant over the frequency band.

Design Considerations

Broadbanding

Southworth[1] published the set of curves shown in Figs. 4 and 5 which indicate the relative phase velocity v/v_0 and the ratio of the energies w_i/w_0 inside and outside of dielectric rods excited in the hybrid HE_{11} mode, which is the mode utilized in these devices. The curves are plotted as functions of the diameter $2a/\lambda_0$ for rods of dielectric constant 10 and 2.5. The curves for $\epsilon = 10$ are of special interest, because this is approximately the dielectric constant of a number of ferrites. Note that for $\epsilon = 10$ in the region $0.15 < 2a/\lambda_0 < 0.4$, the phase velocity rapidly changes from that for free space to near that for an infinite dielectric medium. Note also that in this same transition area the percentage of the total energy within the rod goes from near 0 per cent at $2a/\lambda_0 = 0.15$ to 95 per cent at $2a/\lambda_0 = 0.4$. Hence, for $2a/\lambda_0 > 0.4$, the dielectric rod has very nearly the characteristics of the infinite medium. It has been shown[2] that Faraday rotation in an infinite ferrite medium is independent of frequency subject to the restriction that the magnetizing field is much less than that required for gyromagnetic resonance

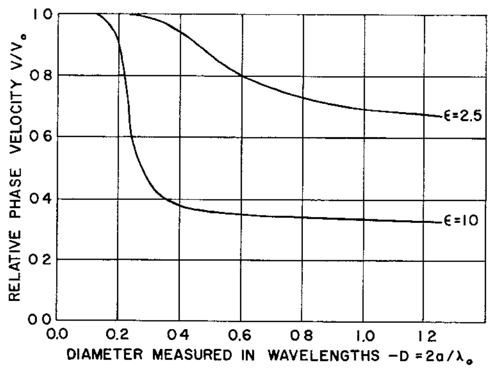

Fig. 4—The relative phase velocity, V/V_0, for the HE_{11} mode in dielectric rod waveguides (from Southworth[1]).

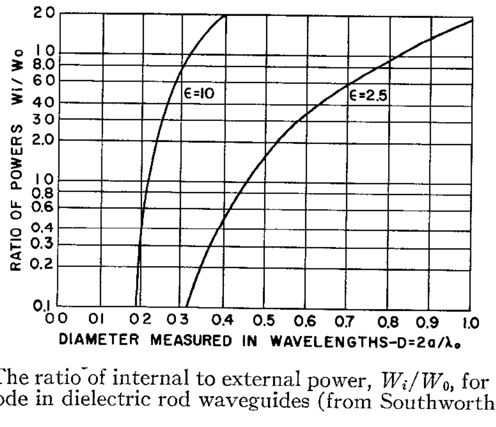

Fig. 5—The ratio of internal to external power, W_i/W_0, for the HE_{11} mode in dielectric rod waveguides (from Southworth[1]).

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[1] G. C. Southworth, "Principles and Applications of Waveguide Transmission," D. Van Nostrand Co., Inc., New York, N. Y., pp. 130–131; 1950.

[2] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications," *Rev. Mod. Phys.*, vol. 25, pp. 253–261; January, 1953.

($H \ll H_0$). The rotation per unit length is given by

$$\theta/l = 4\pi M\gamma\sqrt{\epsilon}/c,$$

where

$\theta/l \equiv$ rotation per unit length
$M \equiv$ ferrite magnetization
$\gamma \equiv$ gyromagnetic ratio
$c \equiv$ velocity of light.

One should also expect rotation to be essentially independent of frequency, subject to the above restriction, for a longitudinally magnetized ferrite dielectric waveguide of diameter $2a/\lambda_0 > 0.4$. (This assumes $\epsilon = 10$. A higher value for ϵ would reduce the diameter required.) In the transition region, the Faraday rotation in a solid rod of ferrite is very frequency dependent, increasing rapidly with increasing frequency. It is interesting to note in passing that there is a similar transition region for ferrite rods in metallic guide. When a ferrite rod diameter is selected which is large enough to provide a good response to the applied field and small enough to avoid the onset of multimoding, it falls into this transition region. This accounts for the frequency dependence of the "conventional" Faraday rotator.

The broad-band rotators described here were designed to be sufficiently large in diameter to provide frequency independent rotation and to be readily machined by standard means, without making the diameter so large as to cause unnecessary losses or to be incompatible with the connecting waveguide. The ferrite diameter used was 0.070 in, which gives $2a/\lambda_0 \cong 0.3$ at 50 kMc. This reduction in diameter from $2a/\lambda_0 = 0.4$ to $2a/\lambda_0 = 0.3$ was permissible because the dielectric constant of the ferrite used was somewhat greater than 10.

Matching

Elsasser[3] pointed out that the HE_{11} mode is readily excited by inserting the end of a dielectric rod into a rectangular waveguide. Indeed, a simple flat or conical taper of the dielectric rod provides a very reasonable broad-band match as indicated in Figs. 2 and 3.

In these devices the tapered dielectric-waveguide transitions serve both as housings for the loss films and as matching sections between the metallic and dielectric waveguides. Faraday rotation in the region of the loss films would degrade the characteristics of the devices; therefore, this part of the dielectric guide must be made of a magnetically inert material. The dielectric constant of this material should, insofar as possible, equal the dielectric constant of the ferrite in order to minimize the mismatch at the ferrite-dielectric interface. A high density alumina was selected because it is a ceramic with many of the mechanical properties of ferrite, has a relatively low loss tangent of ~0.0001, and has a dielectric constant of ~9 which approaches that of the ferrite. Indications are that the discrepancy between the dielectric constants of the ferrite, 10–15, and the dielectric constant of the alumina, 9, is the major contributor to the remaining mismatch of present devices. To achieve better matches in the absence of a more suitable dielectric material for the tapered transitions, it will probably be necessary to adjust the relative diameters of the ferrite and dielectric parts to compensate for the difference in dielectric constants or to step the diameter of one or the other so as to form a step transformer. Ideally the external match should be obtained without resorting to internal mismatches (*e.g.*, step transformers), not only because of bandwidth considerations but also because of the effect of internal mismatches on insertion loss which will be discussed in the next section.

Losses

The minimum insertion loss for these devices is determined by the dielectric losses of the ferrite, wall losses in the connecting metallic guide, losses due to reflection including radiation caused by internal mismatches, and, in the isolator, the departure from the 45° operating rotation. An attempt was made to minimize the dielectric losses by selecting materials with low loss tangents and by keeping the length of the dielectric guide as short as possible. The magnetic losses are probably not very serious since both the saturation magnetization of the ferrite (5000 gauss) and the operating fields are far below the field required for gyromagnetic resonance (~18,000 oe). Experimentally, dielectric guides of solid ferrite exhibit only slightly greater loss than similar guides made of low loss nonmagnetic alumina.

The wall loss quoted by manufacturers for coin silver waveguide of ID 0.074×0.148 in is about 0.04 db per inch in the 50 to 60 kMc band and each device includes 2 or 3 inches of this guide plus two flanges. The metallic guide and flanges on the device actually contribute about 0.20 db to the minimum loss.

When considering losses due to mismatches one must not only take into account the energy reflected from the device, but must also consider radiation from the dielectric waveguide caused by mismatches within the dielectric guide. When solid rods of ferrite or alumina are placed in these devices in place of the composite ferrite and alumina structures the insertion losses are invariably several tenths of a db less than for a composite device of equivalent length. The improvement in the external match can account for no more than a few hundreths of a db. The remainder of the improvement is attributed to the reduction in radiation due to the elimination of the ferrite-dielectric interfaces which are felt to be the major sources of internal mismatch.

Finally the departure from the desired angle of rotation must be considered as a source of forward loss in the isolator. This loss is given in db by

$$L_\theta = -10 \log_{10} \cos^2 (45° - \theta),$$

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[3] W. M. Elsasser, "Attenuation in a dielectric circular rod," *J. Appl. Phys.*, vol. 20, pp. 1193–1196; December, 1949.

where θ is the angle of rotation. It can be seen that L_θ is quite insensitive to small departures from $\theta = 45°$, and the rotation in these devices is so nearly independent of frequency that this source of loss can be neglected if the magnetic field is adjusted to give a 45° rotation at any frequency in the band.

The principal source of the reverse loss in the isolator and the variable loss in the attenuator is absorption in the loss films in the dielectric taper sections. While the resistivity of the film is not critical, experience has shown 100 ohms per square to be a satisfactory value for use in devices at all microwave frequencies. A metallized mica film was chosen because it was available in very thin (0.001 in thick) sheets and was readily cut to the dimensions needed. It would be preferable to deposit the film directly upon the dielectric material of the tapers and eliminate the mica, but this has not yet been done. Assuming efficient loss films, these losses are limited by the departure of the angle of rotation from the optimum angle, the degree to which linear polarization can be maintained, and in the isolator, the mismatch at the interface between the ferrite and alumina. The dependence of the maximum loss of the variable attenuator and the reverse loss of the isolator on the angle of rotation can be written as

$$L_\theta = 10 \log_{10} \csc^2 \Delta\theta,$$

where $\Delta\theta$ is the departure from the optimum angle (45° for the isolator and 90° for the variable attenuator). Isolators with greater than 35 db minimum reverse loss have been built. From the above equation it can be seen that this requires that the rotation be within $\pm 0.5°$ of 45°. Since the interface mismatch and departure from linear polarization both tend to reduce the reverse loss, the rotation must actually be constant to somewhat less than $\pm 0.5°$. This high reverse loss also requires that the linear polarization be kept to a rather high degree.

The dependence of the reverse loss in the isolator upon the interface mismatch comes about in the following way. A reverse wave enters the isolator and undergoes a 45° rotation in travelling to the far end interface where it is partially transmitted and partially reflected. The transmitted wave is absorbed in the far end loss film while the reflected wave undergoes an additional 45° rotation in travelling back toward the near end interface where it is partially transmitted and partially reflected. Once again the transmitted wave is absorbed, and the reflected wave is rotated an additional 45° in travelling back toward the far end. On this pass the reflected wave arrives at the far end polarized perpendicular to the loss film, and the portion transmitted beyond the interface is coupled out into the metallic waveguide. Neglecting the ferrite losses and reflection and radiation losses this transmitted wave is attenuated by just twice the return loss of the ferrite dielectric interface. Thus if the return loss of the interface were 15 db, the maximum reverse loss in the isolator would be only slightly greater than 30 db. Thus it is important to match the interface as well as possible in order to optimize both the forward and the reverse losses of the isolator.

The Dielectric Waveguide Housing

The dielectric guide was housed in a nonconducting housing for two reasons. First, if a conducting cylinder were placed about the dielectric guide, the resulting waveguide would support several modes which would degrade the device characteristics. Second, a conducting cylinder would support eddy currents which slow the response of the device to a changing control field, and a fast response is essential to many variable-attenuator applications. In order to prevent communication between waves internal and external to the dielectric waveguide, a semiconducting carbon loaded phenol fibre was used for the housing. This material is lossy to the microwaves and presents a high resistance to the low frequency eddy currents. The contribution of this RF lossy housing to the minimum insertion loss of the devices is negligible providing its inner diameter is greater than twice the dielectric guide diameter, because over 95 per cent of the microwave energy is confined to the dielectric guide, and the RF fields outside the dielectric guide decay essentially exponentially. An equally satisfactory housing for devices which do not have to be "switched" is a metal cylinder lined with a 0.100 in thick RF lossy cylinder with the above restriction on the internal diameter. The lossy liner alters the boundary conditions at the conducting cylinder wall so as to prevent the propagation of higher modes.

Supporting the Dielectric Guide

The dielectric waveguide must be suspended upon the axis of its housing with its tapers protruding into the rectangular input and output guides. The support should have a dielectric constant much less than that of the dielectric guide so as to minimize its effect on the distribution of energy in the dielectric waveguide, and it should have low losses at millimeter wavelengths. Plastic foams are often employed in devices built to operate at lower frequencies, but they become difficult to work with in the millimeter wave range because of the small dimensions. In these devices, two 0.015 in thick wafers of a low loss plastic of dielectric constant ~ 2.5 which goes under the trade names of Stycast 0005 and Rexolite were used. These wafers are made in the form of circular washers and are placed in metal cups which are attached to each end of the dielectric waveguide housing, and the dielectric waveguide is suspended between them. The supporting wafers are recessed into depressions in the cups which are concentric with the housing and also concentric with machined receptacles for the flanges of the rectangular waveguides. Axial motion of the dielectric waveguide in its supports is prevented by the application of a spot of adhesive at each support.

Magnetic Field Requirements

Unlike gyromagnetic resonance which requires fields of 18 to 20 thousand oersteds at these frequencies, Faraday Rotation occurs for fields between 0 and those required for saturation of the ferrite. The field requirement is minimized by selecting a high saturation ferrite. In this case one need not worry about the saturation being so high as to cause low field losses, because the field required for resonance is three or four times as great as the saturation magnetization of the highest saturation ferrite. A nickel-zinc ferrite of 5000 gauss saturation was chosen and the length of the ferrite was adjusted so that the devices operated with ~30 oe applied field. The resulting ferrite lengths were 0.300 in for the isolator (45° rotation) and 0.500 in for the variable attenuator (0° to 90° rotation). The 30 oe field can be obtained with ~0.25 amps in a solenoid coil of 120 turns over a length of 0.50 in for the attenuator. For the isolator the field required can be obtained with a magnetized rod of Indiana Steel's Alnico V 0.300 long by 0.125 in in diameter brought to within ~0.200 in of the ferrite. In practice both the distance from the ferrite and the angular orientation of the magnet with respect to the axis of the ferrite are made adjustable to provide for a fine adjustment of the field so that the isolator's reverse loss can be optimized.

Magnetic Shielding

Since these devices operate at low fields (30 oe) and are critically dependent upon the operating field, they have been encased in 1/32 in thick μ-metal cylinders which extend over the entire length of the dielectric guides including the tapers and which shield the ferrite from external magnetic fields.

The Variable Attenuator as a Power Leveler

No attempt will be made to itemize the various applications for these two devices, but there is one application of the variable attenuator which should be of considerable interest to anyone engaged in millimeter wave work. The variable attenuator is especially suited for use in an automatic power level control circuit for leveling the output of a backward wave oscillator, for example. In this application the variable attenuator is placed in tandem with the microwave generator. The power out of the attenuator is sampled by means of a directional coupler and a detector, and this level is compared with a reference level. The error between the power level and the reference level is translated into a correction current which is applied to the windings of the variable attenuator. This automatically adjusts the output power level toward the reference level. Several such leveler circuits have been put into operation by this author, A. W. Anderson, and R. V. Goordman, who designed the necessary reference circuits and differential current amplifiers. These circuits have been capable of removing variations of several kc frequency content from the output of BWO's swept over the 50 to 60 kMc band. Fig. 6 shows the effect of leveling on the output of a BWO swept between 50 and 60 kMc.

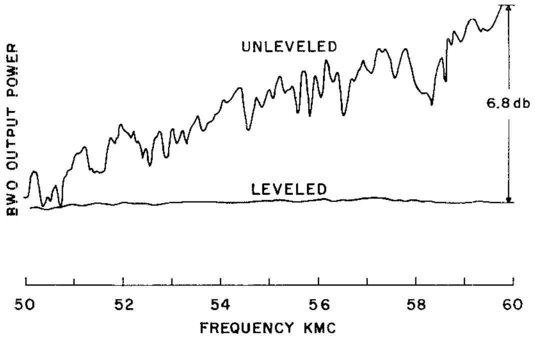

Fig. 6—Millimeter wave power leveling. A comparison of the leveled and unleveled output of a BWO swept from 50 to 60 kMc.

Extension of the Design

There is no apparent reason why the dielectric waveguide rotator should not be readily incorporated into any of the well-known Faraday rotation devices. This type of variable attenuator with similar characteristics has been built at 5.5 kMc and at X band which points up the fact that this design is applicable at any frequency subject to limitations on materials and dimensions. At the lower frequencies one may choose from other excellent broadband rotators such as the dielectrically compensated rotator described by Ohm[4] and the ridged waveguide rotator described by Chait and Sakiotis.[5] However, the simplicity of the dielectric waveguide rotator and the relatively large dimensions of its components tend to make it the most practical for millimeter wave applications.

Acknowledgment

A special commendation goes to A. W. Anderson who carried out the assembly and testing of these devices and their predecessors. His skill and imagination in solving the many mechanical and electrical problems which arose in connection with this effort have been of great value. J. A. Weiss contributed greatly to the development through numerous discussions and suggestions.

Thanks also go to the men in our model shop under A. W. Koenig who prepared the sometimes complicated and always small ferrite and alumina parts.

The author is also indebted to R. V. Goordman for his design of the leveler amplifier which has not only increased the utility of the devices but has increased the facility with which future development work can be carried out.

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[4] E. A. Ohm, "A broad-band microwave circulator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 210–217; October, 1956.

[5] H. N. Chait and N. G. Sakiotis, "Broad-band ferrite rotators using quadruply-ridged circular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 38–51; January, 1959.