Oct. 20, 1959 J. L. DAVIS ET AL 2,909,738

BROADBAND NONRECIPROCAL DEVICES

Filed Aug. 17, 1953 2 Sheets-Sheet 1

FIG. 1

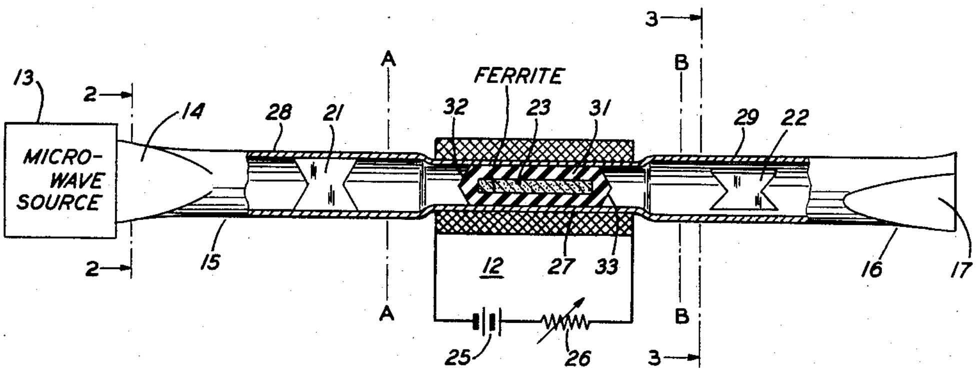

FIG. 4

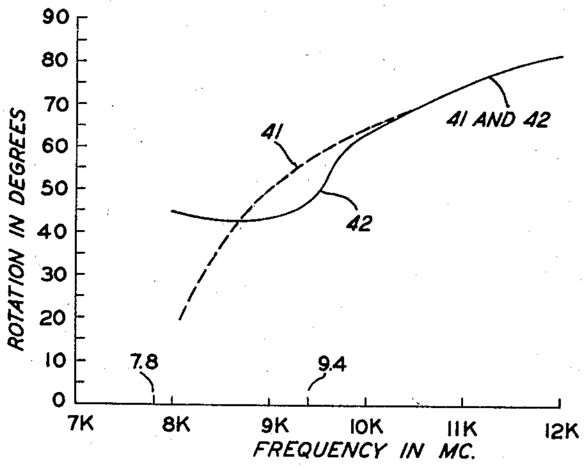

FIG. 2

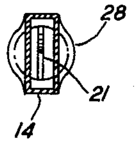

FIG. 3

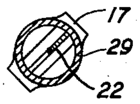

FIG. 5

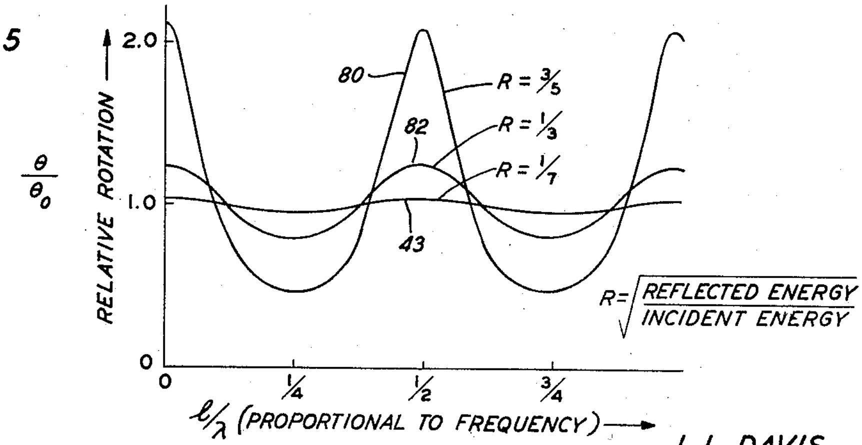

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FIG. 6

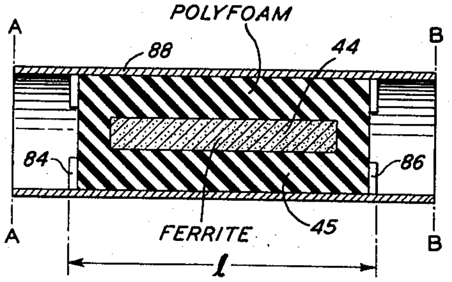


FIG. 7

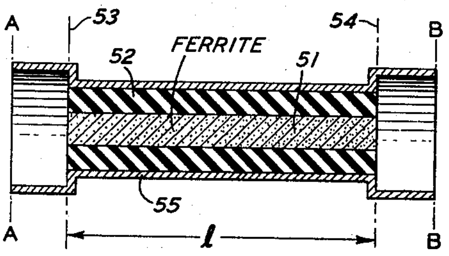


FIG. 8

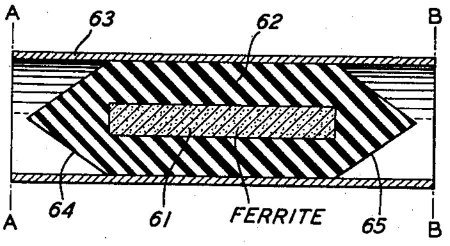
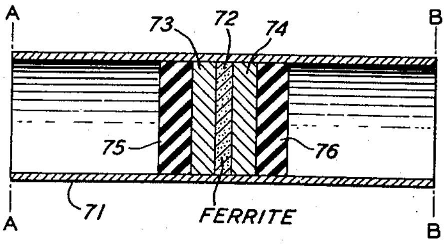


FIG. 9



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BROADBAND NONRECIPROCAL DEVICES

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Application August 17, 1953, Serial No. 374,554
7 Claims. (Cl. 333—98)

This invention relates to broadband nonreciprocal waveguide components.

The theorem of reciprocity states that "In any network composed of linear impedances, if an electromotive force E applied between two terminals produces a current I at some branch in the network, then the same voltage E acting at the second point in the circuit, will produce the same current I at the first point." Most electrical networks, including microwave systems, do obey the theorem of reciprocity and are reciprocal. However, in the last few years a group of nonreciprocal microwave components have been developed which involve the interaction of the electromagnetic wave with a magnetized ferromagnetic medium of low conductivity.

These prior art nonreciprocal devices have frequently employed magnetized polycrystalline ferrites, such as $(NiZn)Fe_2O_3$, to produce the different amount of phase shift or attenuation for the two directions of transmission through the unit. Certain devices of this type are described in C. L. Hogan's article "The Microwave Gyrator" which appeared in vol. 31, pages 1 through 31, of the January 1952 issue of the Bell System Technical Journal. While Hogan showed that in an infinite magnetized medium these nonreciprocal effects are theoretically independent of frequency, in practice it is observed that the electromagnetic propagation characteristics in a waveguide usually cause the effects to be strongly dependent on the microwave frequency. For this reason, the prior art nonreciprocal units are only suitable for use in systems which utilize a relatively narrow band of frequencies.

Accordingly, the principal object of the present invention is to increase the bandwidth of nonreciprocal microwave devices.

In accordance with the invention, operating characteristics of a nonreciprocal electrical device are made substantially constant over a broad frequency band by placing the nonreciprocal element in a section of waveguide having a particular construction. More specifically and in accordance with one embodiment of the invention disclosed in detail hereinafter, a longitudinally magnetized ferromagnetic element is mounted in a resonant section of circular waveguide. The multiple reflections resulting from the resonant nature of the section containing the ferrite can be made to compensate almost entirely for the intrinsic frequency dependence of the ferrite element itself by appropriate choice of the length and the reflection coefficients at the ends of the resonant section.

Other objects and certain features and advantages of the invention will become apparent in the course of the detailed description of the drawings.

In the drawings:

Fig. 1 shows a waveguide system employing a broadband isolator in accordance with the invention;

Figs. 2 and 3 are cross-sectional views in planes through lines 2—2 and 3—3, respectively, of Fig. 1;

Fig. 4 shows plots of rotation vs. frequency for an uncompensated Faraday effect device and for the broadband device of Fig. 1;

Fig. 5 shows several plots which relate the amount of rotation with the characteristics of the resonant section of waveguide;

Figs. 6 and 7 represent alternative structures for securing multiple reflections which may be substituted for the central section of the structure of Fig. 1;

Figs. 8 illustrates a broadband Faraday effect device in which the ferromagnetic pencil is mounted in a body of insulating material having a relatively high dielectric constant; and

Fig. 9 shows an alternative arrangement which is similar in its mode of operation to that of the arrangement of Fig. 8.

Referring more specifically to the drawings, Figs. 1 through 3 show, by way of example and for purposes of illustration, a microwave system including a Faraday effect isolator **12**. A suitable source of microwave energy **13** is coupled to the isolator **12** by means of the rectangular waveguide **14** and the rectangular to round transition section **15**. Another transition section **16** couples the output from the isolator **12** to the rectangular guide **17**, the broad face of which is oriented at an angle of 45 degrees with respect to the board face of the first rectangular guide **14**. The conventional elements of the isolator **12** include the resistive vanes **21** and **22** which are also axially displaced 45 degrees with respect to one another, and aligned with the waveguides **14** and **17**, respectively, and the longitudinally magnetized pencil of ferrite **23**. As may be clearly observed in the cross-sectional views of Figs. 2 and 3, the plane of each of the resistive vanes **21**, **22** is parallel to planes of the broader sides of the respective adjacent rectangular waveguide **14**, **15**. The coil **24** which is energized by a suitable source of voltage **25** via the variable resistance **26** provides the longitudinal magnetic field for the ferrite pencil **23**.

The general mode of operation of a Faraday effect isolator such as is shown in Figs. 1 through 3 is set forth in detail in the article by C. L. Hogan cited hereinbefore, and will be reviewed only briefly here. In short, the two physical principles which are employed are (1) the rotation of the plane of polarization of electromagnetic waves passing through the longitudinally magnetized ferrite element in the same absolute angular direction for both directions of propagation, and (2) the absorption by resistive vanes of electromagnetic waves having the electric vector parallel to the vane. Thus, proceeding from left to right, the electromagnetic wave in the rectangular waveguide **14** is oriented with its electric vector in the horizontal plane parallel to the narrower side walls of the waveguide. Inasmuch as this polarization is retained in the circular guide **28**, the electric vector is perpendicular to the resistive vane **21** and the electromagnetic wave passes through the section of guide containing the resistive vane **21** without attenuation. The longitudinally polarized pencil of ferrite rotates the plane of polarization of the electromagnetic wave 45 degrees clockwise as viewed from left to right, so that the electric vector is now perpendicular to the resistive vane **22** and energy readily passes on into the rectangular waveguide **17**.

When an electromagnetic wave is propagated from right to left in waveguide **17**, however, it is dissipated in the isolator **12** as may be seen from the following analysis. The electric vector will be parallel to the narrower side wall of the rectangular waveguide **17** and thus will be perpendicular to the resistive vane **22** and will not be attentuated by it. In traversing the ferrite pencil **23**, the electric vector will again be rotated clockwise (looking down the axis of the isolator from left to right) into the plane of the resistive vane **21** where it will be absorbed. If the absorption is not complete, the reflected energy will be absorbed by the vane **22**. Therefore, electromagnetic waves applied to waveguide **14** will freely pass through the isolator **12**, but energy applied in the reverse direction from waveguide **17** is dissipated in the isolator.

Before proceeding with the description of Fig. 1, reference is made to the dotted curve **41** of Fig. 4 which shows the normal variation of rotation with frequency for an uncompensated ferrite pencil. Note further that the slope of this dotted curve is so steep that for a 10 percent frequency band centered at 8.8 kilomegacycles the rotation varies more than ±20 percent. With the broad-banding techniques in accordance with the invention, however, as illustrated in the solid line curve **42** of Fig. 4, the Faraday rotation varies less than ±4 percent over a frequency band equal to 15 percent of the center frequency of 8.8 kilomegacycles. This remarkable improvement is obtained by setting up multiple reflections in the region containing the ferrite pencil in accordance with principles to be developed hereinafter.

In the arrangement shown in Figs. 1 through 3, the multiple reflections are set up in the ferrite by making the impedance in the section of guide including the dielectric element **31** substantially less than in the adjoining empty waveguide and by providing the dielectric element **31** with the shallow tapers **32**, **33**. The difference in impedance between the empty and dielectric filled guide is accentuated by constricting the entire central section of waveguide **27** so that at the lower end of the frequency band the frequency of the wave which is transmitted through the isolator is just slightly above the cut-off frequency. Under these conditions the wave impedance in the air-filled pipe will be high. Because the dielectric constant of polystyrene is between 2 and 3, the wave impedance in the polystyrene element **31** which supports the ferrite pencil **23** will be much lower than that in the air-filled region, and the impedance discontinuities will set up multiple reflections in the polystyrene and ferrite region.

The mathematical analysis of the phenomenon by which the multiple reflections broadband the Faraday effect device is exceedingly complicated, and only the results of this analysis in graphical form are presented in this application. In Fig. 5 the ratio,

$$\frac{\theta}{\theta_0}$$

of rotation with multiple reflections, θ compared with rotation without multiple reflections, θ_0, of a ferrite element is plotted against frequency. For convenience the frequency scale is given in terms of

$$\frac{l}{\lambda}$$

where l is the length of the resonant section of waveguide and λ is the wavelength of the electromagnetic waves passing through the section of the waveguide. The series of plots represent a family of curves showing qualitatively the effect of different reflection coefficients at the ends of the resonant section of waveguide. The reflection coefficient is defined as the square root of the ratio of reflected to incident energy, and the three curves **80**, **82** and **43** are plotted for values of reflection coefficient equal to $\frac{3}{5}$, $\frac{1}{3}$ and $\frac{1}{7}$, respectively. The relationship between the reflection coefficient R and the impedances Z_1 and Z_2 in the two sections of the waveguide is as follows:

$$\frac{Z_2}{Z_1}=\frac{1-R}{1+R}$$

Now, by using a resonant cavity of the proper length so that in the desired frequency range the slope of the curves of Fig. 5 is negative, the positive slope of the rotation vs. frequency plot **41** in Fig. 4 may be compensated. For example, between

$$\frac{l}{\lambda}=0 \text{ and } \frac{l}{\lambda}=\frac{1}{4}$$

the slope of all of the plots of Fig. 5 is negative. However, at the low end of this frequency band the length l of the resonant cavity has to be equal to zero, so this range is not as satisfactory as the range between

$$\frac{l}{\lambda}=\frac{1}{2} \text{ and } \frac{l}{\lambda}=\frac{3}{4}$$

At the low and high ends of this frequency band the fixed length l of the resonant cavity is equal to $\frac{1}{2}$ and $\frac{3}{4}$ of the wavelength, respectively. Inasmuch as the curves of Fig. 5 are repetitive, other ranges of

$$\frac{l}{\lambda}$$

may be used where

$$\frac{l}{\lambda}>\frac{n}{2}$$

at the low end of the band and

$$\frac{l}{\lambda}<\frac{2u+1}{4}$$

at the upper end of the frequency band, where n is any integer, usually 1 or 2.

After deciding on the length of the resonant sections of waveguide by the above-noted relationships, the reflection coefficient may be varied to give the appropriate slope in this region. This may be accomplished by varying the taper of the conical surfaces **32** and **33** of the dielectric element **31** of Fig. 1, for example. Normally, as shown in this figure, moderately blunt surfaces are desirable. With higher reflection coefficients, the slopes of the family of curves **80**, **82** and **43** of Fig. 5 get steeper, and more compensation is obtained. The variable length of the resonant waveguide section therefore constitutes a means for determining the sign of the compensation and the reflection coefficient at the ends of the resonant section constitutes a means for determining the slope of the compensation.

Figs. 6 and 7 represent alternative structures which may be substituted for the central resonant section of the isolator **12** of Fig. 1. Specifically, in Fig. 6 the multiple reflections are obtained by the use of the irises **84** and **86** which are separated by the critical distance "l" as noted above. In the section of waveguide **88** between the two irises, the pencil of ferrite **44** is mounted in a dielectric element **45** which may be made, for example, of polyfoam, an aerated polystyrene composition which has a dielectric constant very nearly equal to unity. The ferrite pencil could also be supported by cylinders or washers of other dielectric materials such as teflon or polystyrene. In this structure of Fig. 6, the magnitude of the reflection coefficient is determined largely by the size of the aperture in the irises. In Fig. 7 the pencil of ferrite **51** is mounted in a tube **52** of solid dielectric material, and the multiple reflections are set up at the discontinuities **53**, **54** where these elements terminate. The additional factor of the abrupt change in the diameter of the waveguide **55**, from its small size between the discontinuities **53**, **54** to its larger size on either side of this dielectric and ferrite filled region, increases the reflection coefficient at the discontinuities.

The structures of Figs. 8 and 9 are similar to those of Figs. 1, 6 and 7 in that they broaden the frequency band of a Faraday effect rotator, but operate on a different principle. Referring to Fig. 4, it may be observed that at higher frequencies far above the cut-off frequency of the waveguide (about 7.8 kilomegacycles in Fig. 4), the slope of the combined curves **41** and **42** decreases and tends toward the horizontal. The Faraday effect devices of Figs. 8 and 9 secure a relatively little change of rotation over a broad frequency band by operating far above cut-off. This desirable feature is accomplished without increasing the waveguide size by having the active portion of the microwave rotator made of very high dielectric constant material.

In Fig. 8 the central pencil of ferrite **61** is made of a ferrite such as a nickel zinc ferrite which has a dielectric constant of approximately 10, which is typical of the large majority of ferrites. It is mounted in a cylinder of dielectric material **62** having substantially the same dielectric constant as that of the ferrite with the cylinder in turn being mounted in the waveguide **63**. This cylinder **62** is tapered at **64** and **65** to improve the match with the air-filled waveguide. Under these conditions the cut-off wavelength in the ferrite and dielectric filled portion of the waveguide is approximately five times as great as the wavelength in this portion of the waveguide. Furthermore, the radial distribution of the electromagnetic field will not change appreciably with frequency because, neglecting the small difference in the permeabilities of the ferrite and dielectric materials, the waveguide is filled with a uniform dielectric.

Fig. 9 shows an alternative arrangement to that of Fig. 8 in which the waveguide **71** is operated far above cutoff. In this system the ferrite element **72** is in the form of a disc completely filling the waveguide. On either side of the ferrite element are discs **73**, **74** of a suitable permanent magnet material such as barium ferrite which is made from barium oxide and iron oxide. When these permanently magnetized discs are used to apply the magnetic field to the ferrite, the magnetizing coil **24** of Fig. 1 may naturally be dispensed with. The dielectric discs **75**, **76** at either extreme of the assembly are quarter-wave matching plates to match the air-filled waveguide to the ferrite-filled section.

While all of the embodiments of the invention discussed hereinbefore have the advantage of broadbanding the Faraday rotation, the structures of Figs. 1, 7 and 8 in which the ferrite pencil is mounted in dielectric material having a fairly high dielectric constant, have the additional advantage in the absolute increase in rotation at all frequencies. The physical reasons for this increase become apparent from the formula for the rotation and an analysis of the conditions in the guide. The rotation per unit length in an infinite magnetized medium is given by the relation

$$\frac{\theta}{l}=\frac{\omega}{c}\sqrt{\epsilon}(\sqrt{\mu_-}-\sqrt{\mu_+})$$

where $\mu\pm$ are the effective permeabilities seen by the circularly polarized components of the wave,

$$\frac{\theta}{l}$$

is the rotation per unit length, ω is the angular frequency, c is the velocity of light and ϵ is the dielectric constant. The same relation applies to the guided wave if $\mu\pm$ and ϵ are the effective values averaged over the entire waveguide mode. Thus by increasing the dielectric constant of the region surrounding the ferrite the average value of ϵ is increased. Since the radial distribution is also changed in such a way as to reduce the fraction of the power contained in the ferrite, the increase in rotation is less than is obtained when the waveguide diameter is reduced at the same time.

Although the Faraday effect element has been termed ferrite material at many points in the foregoing specification, other ferromagnetic materials having low conductivity may be employed. Specifically, very finely divided conducting magnetic powder in an insulating matrix exhibits a substantial Faraday effect. One example of a ferrite material which has proved eminently satisfactory is the polycrystalline nickel-zinc ferrite $(\mathrm{Ni}_{.3}\mathrm{Zn}_{.7})\mathrm{Fe}_2\mathrm{O}_3$. When the term "low conductivity" is employed in the present specification and claims, the material in question is considered to have an over-all resistivity of 100 ohm-centimeters or more.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a Faraday effect rotator having a normal rotation versus frequency characteristic, a waveguide, a resonant waveguide section connected in series with said waveguide, a pencil of ferrite within and generally aligned with said resonant waveguide section, means applying a longitudinal magnetic field to said pencil of ferrite, means for introducing electromagnetic waves of a predetermined group of wavelengths into said waveguide, all of said predetermined group of wavelengths being less than twice but greater than four-thirds the length of said resonant waveguide section and reflection means at each end of said resonant waveguide section for providing a compensating rotation versus frequency characteristic the slope of which is substantially equal and opposite to that of said normal rotation versus frequency characteristic.

2. In a Faraday effect rotator for operation over a broad band of frequencies having a normal rotation versus frequency characteristic, a waveguide, a resonant waveguide section connected in series with said waveguide, a pencil of ferromagnetic material of low conductivity within said resonant waveguide section, means for applying a longitudinal magnetic field to said pencil of ferromagnetic material, the relationship between the electromagnetic waves in said band of frequencies and the length of the resonant waveguide section being such that the wavelengths of said electromagnetic waves are less than twice but greater than four-thirds the length of said resonant waveguide section, and reflection means at each end of said resonant waveguide section for providing a compensating rotation versus frequency characteristic the slope of which is substantially equal and opposite to that of said normal rotation versus frequency characteristic.

3. In a Faraday effect rotator having a normal rotation versus frequency characteristic, a waveguide, a resonant waveguide section connected in series with said waveguide, a pencil of ferromagnetic material of low conductivity within said resonant waveguide section, means applying a longitudinal magnetic field to said pencil of ferromagnetic material, means for introducing electromagnetic waves of a predetermined group of wavelengths into said waveguide, all of said group of wavelengths being less than

$$\frac{2}{N}$$

but greater than

$$\frac{4}{2N+1}$$

times the length of said resonant waveguide section, where N is an integer, and reflection means at each end of said resonant waveguide section for providing a compensating rotation versus frequency characteristic the slope of which is substantially equal and opposite to that of said normal rotation versus frequency characteristic.

4. In a nonreciprocal microwave component, a waveguiding structure, means for introducing electromagnetic waves of a predetermined group of wavelengths into said waveguiding structure, a magnetically polarized element of ferromagnetic material disposed in the path of electromagnetic wave energy supported by said structure, said element having a normal variation of non-reciprocal effect with frequency, multiple reflective means including two impedance discontinuities located on either side of said polarized element for compensating for said variation, the relationship between said electromagnetic waves and the distance between said discontinuities being such the distance between said discontinuities falls within the range of three-quarters to one-half times the wavelengths of said electromagnetic waves.

5. In a Faraday effect polarization rotator having a normal rotation versus frequency characteristic, a waveguide, a resonant waveguide section connected in series with said

waveguide, said resonant section being resonant to wave energy polarized in all possible planes of polarization, a pencil of ferromagnetic material of low conductivity within said resonant waveguide section, means for applying a longitudinal magnetic field to said pencil of ferromagnetic material, means for introducing electromagnetic waves of a predetermined group of wavelengths into said waveguide, all of said group of wavelengths being less than

$$\frac{2}{N}$$

but greater than

$$\frac{4}{2N+1}$$

times the length of said resonant waveguide section, where N is an integer, and reflective means at each end of said resonant waveguide section fixing said length of said resonant section.

6. In a Faraday effect rotator having a normal rotation versus frequency characteristic, a hollow substantially circular conducting wave guide, an element of ferrite located therein, a magnet for applying a longitudinal field to said ferrite element closely coupled therewith, means for introducing electromagnetic waves of a predetermined group of wavelengths into said wave guide, and reflection means including the blunt ends of an element of dielectric material enclosing said ferrite element for providing a compensating rotation versus frequency characteristic the slope of which is substantially equal and opposite to that of said normal rotation versus frequency characteristic, the relationship between said electromagnetic waves and the distance between said blunt ends being such that the distance between said blunt ends falls within the range of

$$\frac{2N+1}{4} \text{ to } \frac{N}{2}$$

times the wavelengths of said electromagnetic waves, where N is an integer.

7. In a Faraday effect rotator for operation over a broad band of frequencies having a normal rotation versus frequency characteristic, a wave guide, a pencil of ferrite in the wave guide, means for longitudinally magnetically polarizing said ferrite pencil, and reflection means including a hollow cylinder of dielectric material encircling and supporting said ferrite pencil for providing a compensating rotation versus frequency characteristic the slope of which is substantially equal and opposite to that of said normal rotation versus frequency characteristic, said cylinder having a relative dielectric constant greater than two and having blunt end surfaces, the relationship between the electromagnetic waves in said band of frequencies and the distance between said blunt ends being such that the distance between said blunt ends falls within the range of

$$\frac{2N+1}{4} \text{ to } \frac{N}{2}$$

times the wavelengths of said electromagnetic waves, where N is an integer.

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