A Nonreciprocal Tunable Waveguide Directional Filter Using a Turnstile Open Gyromagnetic Resonator

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Abstract—**The 4-port waveguide directional filter is a classic network in microwave engineering. The purpose of this paper is to describe one gyromagnetic version using an open gyromagnetic resonator in a dielectric-filled cavity. A property of the circuit is that it behaves as a 4-port circulator with one direction of circulation at one split frequency of the resonator and with the other direction for the other split frequency. An insertion loss between the coupled ports below 1.50 dB and an attenuation or isolation of typically 15 dB between the decoupled ports over most of the tuning range of the filter have been achieved. Its 3-dB bandwidth is typically 65 MHz. A typical tuning range of more than 1 GHz centered at about 10.5 GHz has been separately realized for each split branch.**

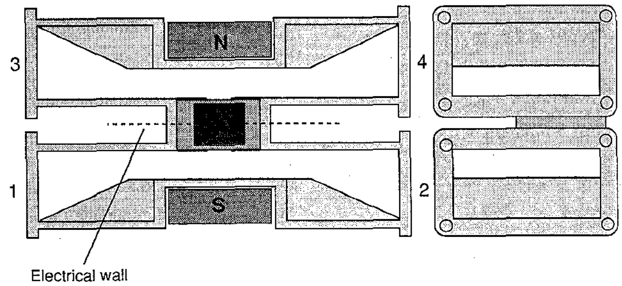

Fig. 1. Four-port tunable nonreciprocal directional filter using half-wave long gyromagnetic resonator.

I. Introduction

An important application of magnetic insulators at microwave frequencies is in the design of tunable filters. Such a gyromagnetic filter may be incorporated into the design of a tunable directional filter. One classic arrangement consists of two rectangular waveguides coupled at the planes of circular polarizations of the alternating magnetic field by a YIG sphere in the common waveguide wall [1]–[4]. One difficulty with this class of filter, however, is the onset of spinwave instability, which can occur even at signal levels of a few milliwatts [5], [6]. In the geometry evaluated in this paper the YIG resonator is replaced by a half-wave gyromagnetic resonator with quasi-open magnetic walls in a dielectric-filled cavity. This configuration is illustrated in Fig. 1. A related high-power version has also been described in [3], [7]. A cylindrical resonator with an open sidewall and electric end walls has also been proposed [4].

The reciprocal part of this circuit consists of primary and secondary rectangular waveguides coupled by circular apertures to a half-wave long circular waveguide whose axis coincides with the position at which the alternating magnetic fields in the rectangular waveguides are circularly polarized [8], [9]. A feature of the nonreciprocal version of this 4-port circuit is that it has the properties of a 4-port circulator with one sense of circulation at one split frequency of the gyromagnetic resonator and another sense at the other split frequency. The filter displays bandpass responses between one pair of ports and all pass responses between the other one pair. In its demagnetized state, it behaves as a reciprocal directional filter without any isolation properties. The cavity is detuned at any other frequency and the primary and secondary waveguides are decoupled.

Some works related to that outlined in this paper are noted in [10]–[15].

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II. Equivalent Circuit of Nonreciprocal Directional Filter

The 4-port tunable filter discussed in this paper differs from the conventional YIG filter in that it behaves as a 4-port circulator with one direction of circulation at one split frequency of the gyromagnetic resonator and with another direction for the other split frequency. Each possibility has two paths that display all-pass responses and two paths that have band-pass ones. The primary and secondary waveguides are separately decoupled at all frequencies other than the split frequencies. If the gyromagnetic resonator is demagnetized, then the network displays reciprocal bandpass characteristics between ports 1 and 4 and between ports 2 and 3 and exhibits reciprocal bandstop characteristics between ports 1 and 2 and between ports 3 and 4. These four situations are summarized in Fig. 2. If the sense of the direct magnetic field used to magnetize the gyromagnetic resonator is reversed, then the senses of circulation indicated in Fig. 2 are interchanged. This situation is summarized in Fig. 3.

An understanding of this sort of circulator has to take into account the fact that each split field pattern rotates in opposite directions. If both the frequency and the hand of polarization of a signal in one waveguide coincide with those

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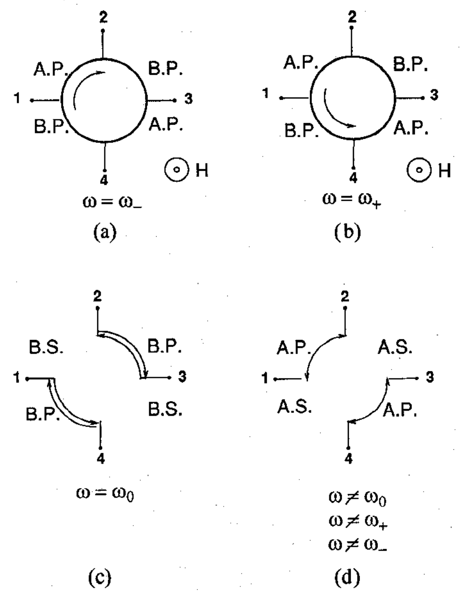

Fig. 2. A.P.—all = pass filter; A.S.—all = stop filter; B.P.—band = pass filter; B.S.—band = stop filter. (a) Equivalent circuit of tunable filter at lower split frequency of gyromagnetic resonator. (b) Equivalent circuit of tunable filter at upper split frequency of gyromagnetic resonator. (c) Equivalent circuit of tunable circuit at frequencies other than split frequencies of gyromagnetic resonator. (d) Equivalent circuit of reciprocal directional filter.

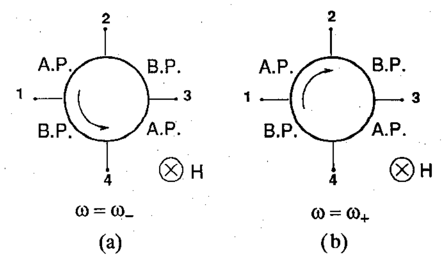

Fig. 3. (a) Equivalent circuit of tunable filter at lower split frequency of gyromagnetic resonator. (b) Equivalent circuit of tunable filter at upper split frequency of gyromagnetic resonator.

of the gyromagnetic resonator, then it is coupled to the other waveguide. If either the frequency or the polarization does not coincide, then it is not coupled. If, for example, the frequency of a signal at port 1 in the primary waveguide coincides with the upper split frequency of the gyromagnetic resonator, and if it establishes a circularly polarized field at the coupling iris with the same sense as that of the corresponding gyromagnetic mode, then it will be coupled to port 4 in the secondary waveguide by the resonator. For a signal at port 4 in the secondary waveguide, the other normal mode of the resonator is established. The frequencies of the gyromagnetic resonator and the signal are in this instance different, and no coupling occurs between the two waveguides. Such a signal is therefore emergent at port 3 in the same waveguide. This situation may be understood by observing that the resonant frequencies of the cavity are different for clockwise and counterclockwise rotating magnetic fields. Similar considerations indicate that an incident signal at port 3 emerges at port 2 and that one at port 2 emerges at port 1. The scattering parameters of the nonreciprocal directional filter are therefore in keeping with

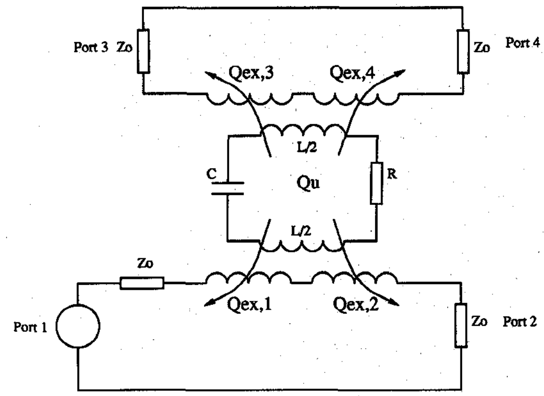

Fig. 4. Phenomenological model of directional gyromagnetic resonator [11].

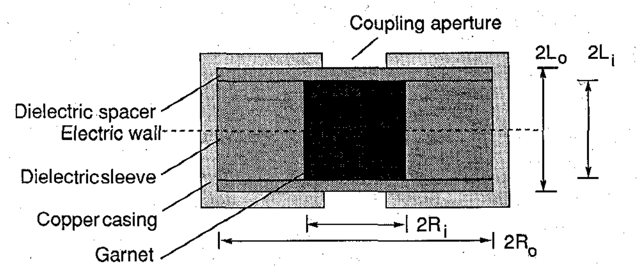

Fig. 5. Transmission cavity resonator using half-wave long gyromagnetic resonator.

those of a 4-port circulator. In a fixed field device it embodies both filter and circulator properties.

One possible phenomenological equivalent circuit of a 4-port directional filter consists of four transmission lines coupled by a series resonator in the manner indicated in Fig. 4. The scattering matrix of this arrangement has been deduced in [12].

4-port tunable YIG filters using physical 3-dB hybrids have been separately described in [13], [14].

III. Gyromagnetic Turnstile Resonator

The gyromagnetic resonator employed in the construction of the nonreciprocal directional filter outlined in this work consists of a cylindrical half-wave long open gyromagnetic resonator embedded in an oversized dielectric-filled metal enclosure with coupling apertures on the two lateral flat faces. Its schematic diagram is illustrated in Fig. 5. One possible model for its central region is a half-wave long section of gyromagnetic waveguide supporting a hybrid pair of degenerate or split HE_{11} counter-rotating modes. The flat circular disks on either side of the main region ensure an open wall boundary condition at the two open flat faces. The microwave effect of each of these sections is absorbed in the coupling mechanism at either end of the assembly. The tuning range of this type of resonator may be specified once its mode chart and split frequencies have been established and once the logic of the direct magnetization is fixed. The three possibilities are a negative excursion of the direct magnetic field, a positive one, or a sweep straddling both senses of the direct field.

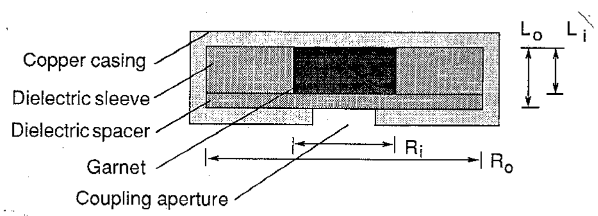

Fig. 6. Reflection cavity resonator using quarter-wave long gyromagnetic resonator.

Propagation along the main section of the resonator is usually described by plotting β/k_0 versus k_0R_i with R_i/R_0 and $\varepsilon_f/\varepsilon_d$ as parameters, this is the approach adopted in this work. The required relationship may be deduced by making use of that between the propagation constant (β) and the guide wavelength (λ_g).

$$\beta = \frac{2\pi}{\lambda_g} \tag{1}$$

If a cavity resonator arrangement is employed to deduce the relationship between β/k_0 and k_0R_i and if the effect of the semi-ideal lateral walls of the main section is neglected then

$$\lambda_g = 4L_i \tag{2}$$

so that

$$\beta = \frac{\pi}{2L_i} \tag{3}$$

The wavenumber (k_0) is separately related to the free space wavelength (λ_0) of the resonator by

$$k_0 = \frac{2\pi}{\lambda_0} \tag{4}$$

The magnetic walls at the two flat faces of the cylindrical gyromagnetic region are enforced by dielectric spacers. The thickness of each end spacer is usually described by defining a filling factor k. This quantity is fixed as

$$k = \frac{L_i}{L_0} \tag{5}$$

ε_f and ε_d are the relative dielectric constant of the ferrite and that of the surrounding dielectric of the cavity, respectively.

Although there is much practical and theoretical guidance in the literature in connection with the design of this sort of resonator, its details have been chosen semiempirically. Some background material on this type of resonator is available in [16]–[21].

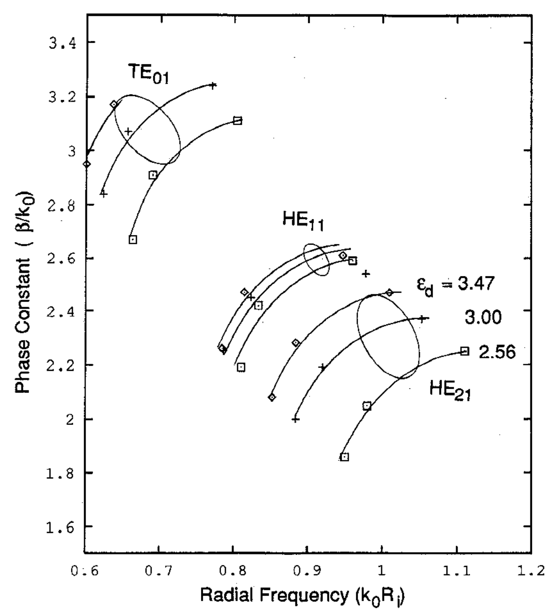

Fig. 7. Relationship between k_0R_i and β/k_0 for demagnetized gyromagnetic resonator for parametric values of $\varepsilon_d (k \approx 0.80)$.

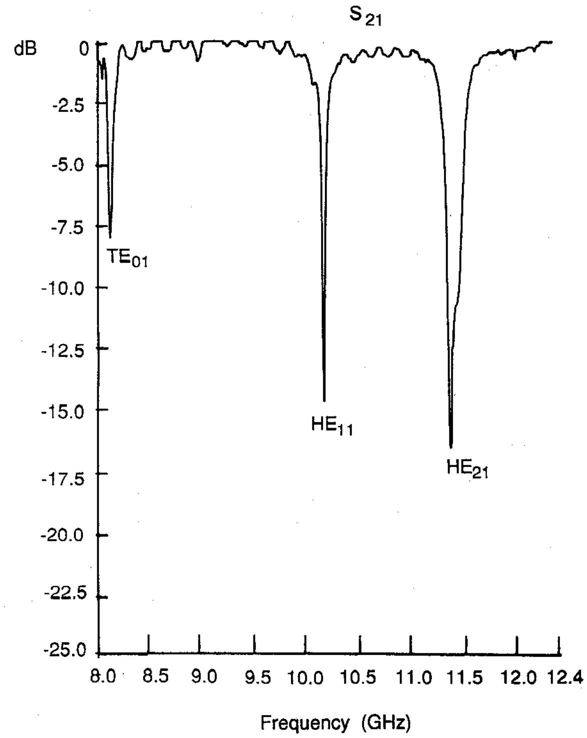

Fig. 8. Frequency response of demagnetized quarter-wave long gyromagnetic resonator $(k \approx 0.80, \varepsilon_d = 3, \varepsilon_f = 15.1, R_i/L_i = 1.283)$.

IV. Experimental $HE_{11\,1/2}$ Mode Chart

The experimental construction of the mode chart of the cavity under consideration can be done by having recourse either to a 1-port reflection arrangement or to 2-port or 4-port transmission ones. The 1-port arrangement adopted here is obtained by introducing an electric wall through the plane of symmetry of the cavity. Its geometry is indicated in Fig. 6.

A family of experimental mode charts in the 8–12 GHz band is summarized in Fig. 7. It indicates that, with the choice of experimental parts adopted in this work, there exists a mode both above and below the dominant $HE_{11\,1/2}$. While the mode chart of the dominant mode is not too affected by the choice of the relative dielectric constant of the dielectric filler, those on either side of it are more influenced by it. This information is sometimes conveyed by plotting k_0R_i against R_i/L_i instead of k_0R_i versus β/k_0. A typical frequency response is indicated in Fig. 8.

The effect of the filling factor upon the mode chart is separately illustrated in Fig. 9. The usual tuning effect of a metal wall in proximity with the open lateral wall of a dielectric res-

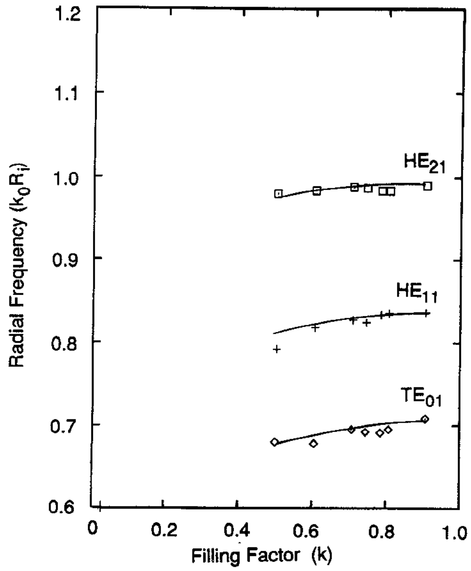

Fig. 9. Relationship between filling factor k and $k_0R_i(\varepsilon_d = 2.56, \varepsilon_f = 15.1, R_i/L_i = 1.283)$.

onator is not apparent in this data. The reason for the absence of this feature may be due to the fact that the diameter of the coupling aperture (9.0 mm) exceeds that of the gyromagnetic element of the resonator (7.74 mm). The filling factor for each assembly has been separately fixed on the basis of experience as

$$k \approx 0.80$$

The effect of this quantity upon the coupling between the circular cavity and the rectangular waveguide has not been investigated.

The metal enclosure employed in this work is described by its radius (R_0) and length (L_0) and by its aspect ratio

$$R_0 = 7.00 \text{ mm}$$
$$L_0 = 3.80 \text{ mm}$$
$$\frac{R_0}{L_0} = 1.84$$

The three resonator geometries employed in this work are described by

$$R_i,\ L_i = 3.72 \text{ mm},\ 3.30 \text{ mm}; \qquad R_i/R_0 = 0.53$$
$$R_i,\ L_i = 3.72 \text{ mm},\ 2.89 \text{ mm}; \qquad R_i/R_0 = 0.53$$
$$R_i,\ L_i = 4.77 \text{ mm},\ 3.00 \text{ mm}; \qquad R_i/R_0 = 0.68$$

The ratio R_i/R_0 is 0.53 for two of the resonators and is 0.68 for one of them. While it is not strictly appropriate to describe by a single curve assemblies with different values of R_i/R_0, it has nevertheless been done here. This difficulty arose due to a lack of foresight in implementing the hardware during the experimental phase of the work. The assumption employed in doing so may be deemed valid provided the fields in the resonator may be assumed to decay rapidly from the central region, so that the position of the outside waveguide wall may be neglected in calculating the phase constant of the main section.

The relative dielectric constants of the three dielectric fillers utilized here are $\varepsilon_d = 2.56$, $\varepsilon_d = 3.0$, and $\varepsilon_d = 3.47$, respectively. The garnet material employed in this work had a magnetization M_0 of 0.1600 T and a relative dielectric constant (ε_f) of 15.1.

If the direct magnetic field sweep establishes the lower branch of the split HE_{11} modes, then it would seem that a suitable value for the relative dielectric constant of the dielectric filter should be less than $\varepsilon_d = 2.56$. If it establishes the upper branch, then a suitable value is $\varepsilon_d = 3.47$. If the excursion of the direct magnetic field straddles both split modes, then an appropriate value for the dielectric filler is $\varepsilon_d = 2.56$. The latter value in conjunction with a resonator with an aspect ratio of $R_i/L_i = 1.283$ has in fact been adopted in the final design. Its complete details are summarized in the section on the 4-port device.

The experimental data obtained here may be verified in one instance by having recourse to one solution based on the related waveguide problem in [22]–[26].

$$\beta/k_0(k_0R_i, R_i/R_0, \varepsilon_f/\varepsilon_d) = 2.93(0.76, 0.53, 5)$$

The solution obtained here with the same geometry is

$$\beta/k_0(k_0R_i, R_i/R_0, \varepsilon_f/\varepsilon_d) = 2.25(0.76, 0.53, 5)$$

In comparing these two sets of entries it is notable that no account has been taken of the fact that the relative permeability (μ_d) of a demagnetized ferrite material is different from unity. μ_d is given as 0.845 at 9300 MHz for a material with a magnetization of 0.1600 T. The influence of the dielectric spaces on either side of the gyromagnetic section also has not been considered.

Some additional scrutiny of this work suggests that one geometry worthy of consideration in any future work is defined by

$$\beta/k_0(k_0R_i, R_i/R_0, \varepsilon_f/\varepsilon_d) = 2.14(0.76, 0.40, 5)$$

The value used in this work is

$$\beta/k_0(k_0R_i, R_i/R_0, \varepsilon_f/\varepsilon_d) = 2.40(0.84, 0.53, 5.9)$$

Once $\varepsilon_f/\varepsilon_d$ is chosen, then R_i is fixed from a statement of k_0 and k_0R_i, L_i is set from a knowledge of β/k_0. The cavity dimensions L_0 and R_0 are separately obtained from statements of k and R_i/R_0.

V. Odd and Even Mode Networks

The adjustment of the sort of junction considered in this paper separately requires that the position of the coupling aperture in the rectangular waveguide be fixed and that the coupling between the circular cavity and each rectangular waveguide be optimized. Since many of the properties of 4-port symmetrical circuits may be deduced by forming its odd and even mode circuits, this approach has been adopted in this work in order to study some of the features of the junction under consideration. The even mode at the rectangular waveguide ports establishes an open circuit at the symmetry plane of the gyromagnetic resonator, while the odd mode establishes a short-circuit there. These two possibilities are

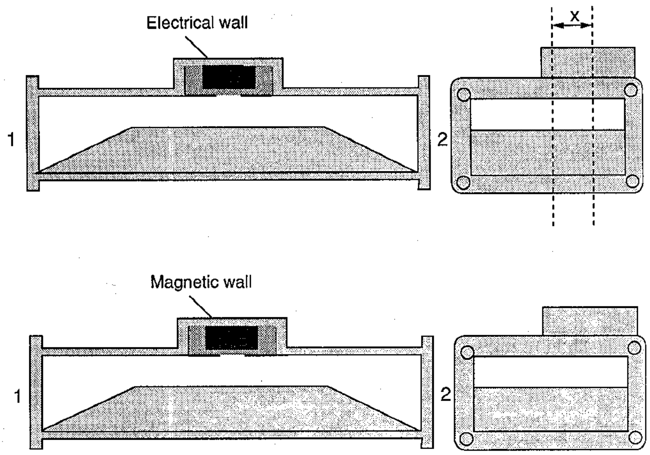

Fig. 10. (a) Even mode circuit of nonreciprocal directional filter. (b) Odd mode circuit of nonreciprocal directional filter.

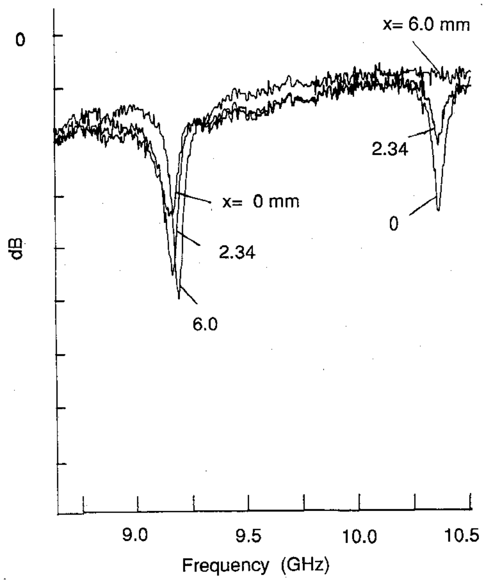

Fig. 11. Magnitude of split modes against position across rectangular waveguide using magnetized gyromagnetic resonator (7 mm iris).

illustrated in Fig. 10. The odd mode geometry is readily constructed and so it has been adopted in this work. It has also been used to verify the tuning range of the gyromagnetic resonator, to be described in the next section.

The position of the gyromagnetic resonator on the wide dimension of the rectangular waveguide was fixed by moving the resonator across the waveguide. The frequency responses of the two split modes for one value of the direct magnetic field and three different positions of the resonator are illustrated in Fig. 11.

The parameters affecting the coupling between the rectangular waveguide and the gyromagnetic resonator in the 2-port arrangement were experimentally adjusted in order to proceed with some preliminary measurements. This was done by varying both the size of the coupling aperture and the impedance level of the rectangular waveguide in the coupling region. The reduced height waveguide section was separately matched to standard waveguide (WR 90) by means

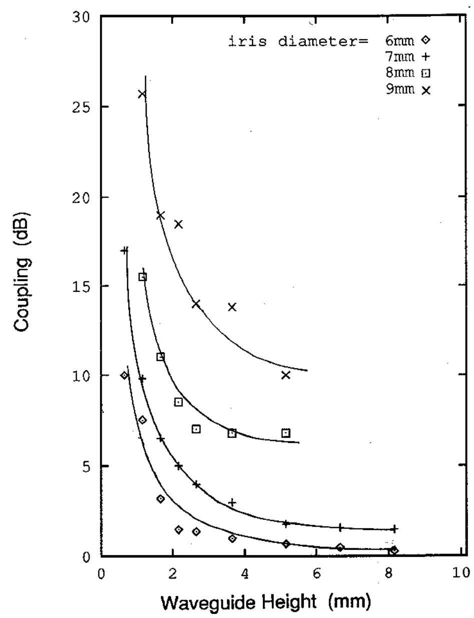

Fig. 12. Experimental relationship between waveguide height and degree of coupling between rectangular waveguide and gyromagnetic resonator for different coupling irises.

of simple impedance tapers. A summary of this adjustment is depicted in Fig. 12. The solution adopted in this work for engineering purposes is an under-coupled one. Its details are: a coupling aperture with a diameter of 9.0 mm and a waveguide section with a narrow dimension of 5.25 mm. It was subsequently reset in the 4-port configuration, again on the basis of experiment.

VI. Split Frequencies of Gyromagnetic Resonator

The split frequencies of the gyromagnetic resonator may be experimentally determined using the odd-mode 2-port arrangement by either placing it at the symmetry plane of the waveguide or locating it at one of the planes of circular polarization of the alternating magnetic field. The former location was in fact chosen in this work. Figure 13 indicates the result obtained for a gyromagnetic resonaor for which the relative dielectric constant of the dielectric filler is $\varepsilon_d = 3.47$ and for which $R_i/L_i = 1.283$. Each branch on this illustration is obtained with a different sense of the direct magnetic field. Figure 14 depicts a similar result but with the same gyromagnetic resonator embedded in a dielectric filler equal to $\varepsilon_d = 2.56$. Since the upper branch of the split $\mathrm{HE}_{11\,1/2}$ modes does not, in the latter circuit, intersect the higher pair of split HE_{21} modes, it was adopted for engineering purposes.

The overall frequency response of the device can be extended to encompass both split branches by sweeping the direct field between its positive and negative settings. This feature may be understood by recalling that a gyromagnetic waveguide displays one value of permeability for a circularly polarized wave with the direct magnetic field along that of propagation and a second value if the direct magnetic field is in the opposite sense from that of propagation. Figure 15 summarizes the relationships between frequency and direct magnetic field for the two arrangements utilized here. It indicates a typical tuning

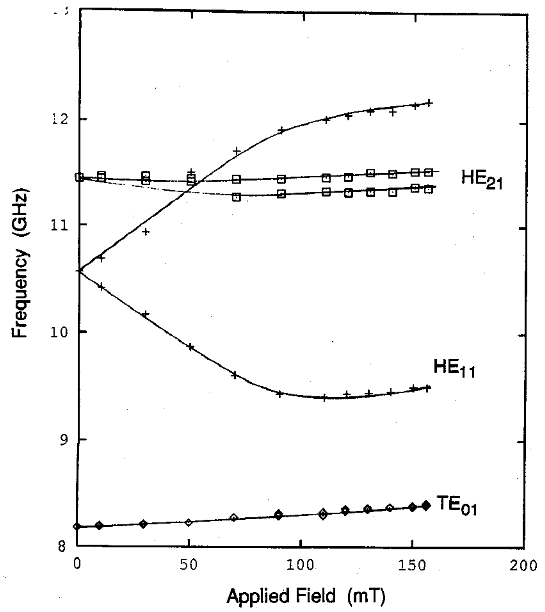

Fig. 13. Split modes in quarter-wave long gyromagnetic resonator ($\varepsilon_d = 3.47, \varepsilon_f = 15.1, M_0 = 0.1600$ T, $R_i/L_i = 1.283$).

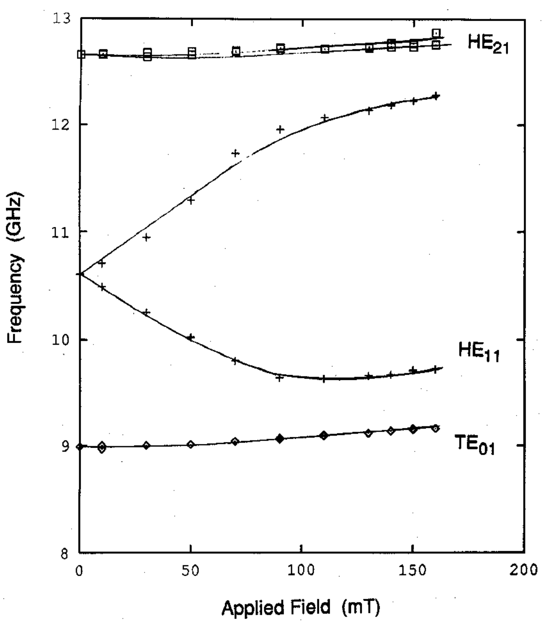

Fig. 14. Split modes in quarter-wave long gyromagnetic resonator ($\varepsilon_d = 2.56, \varepsilon_f = 15.1, M_0 = 0.1600$ T,$\mathrm{R_i/L_i} = 1.283$).

range of 2 GHz centered at about 10.50 GHz. The tuning range of either assembly may in all likelihood be further extended by utilizing a ferrite material with a magnetization of, for example, 0.2400 T instead of the value of 0.1600 T used in this work.

The description of propagation in a circular waveguide containing a magnetized gyromagnetic rod and that in an open gyromagnetic resonator have been the subject of much literature. The exact formulation of the waveguide problem has been dealt with in [21]–[26]. Various approximate solutions in the case of the magnetized resonator problem are separately given in [27]–[29]. One upper bound for the split frequencies

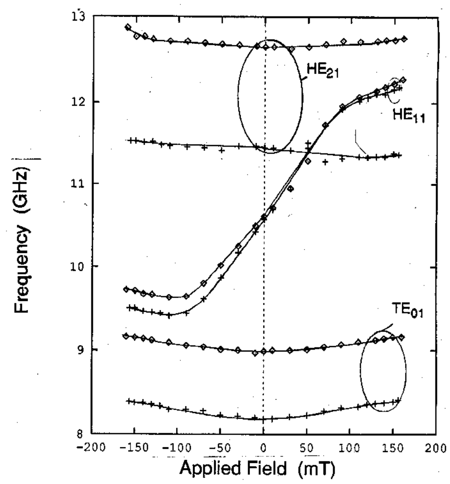

Fig. 15. Tuning ranges of gyromagnetic resonator ($\varepsilon_d = 2.56$ and 3.47, $\varepsilon_f = 15.1, k \approx 0.80, M_0 = 0.1600$ T, $\mathrm{R_i/L_i} = 1.283$).

of the $\mathrm{HE}_{11\,1/2}$ modes in an open gyromagnetic resonator, which is based on perturbation theory, may be derived by having recourse to the split phase constants of this type of waveguide.

$$\beta_{\pm}^2 \approx k_0^2 \varepsilon_{\text{eff}}(1 \pm C_{11}\kappa) - \left(\frac{1.84}{R}\right)^2 \quad (6)$$

where

$$C_{11} = \frac{2}{(1.84)^2 - 1} \quad (7)$$

ε_{eff} is an effective dielectric constant and κ is the off-diagonal element of the tensor permeability.

If a half-wave long cavity is formed from such a waveguide then

$$\beta_+ = \beta_- = \text{const}$$

and

$$k_+^2 \varepsilon_{\text{eff}}(1 - C_{11}\kappa) - \left(\frac{1.84}{R}\right)^2 = k_-^2 \varepsilon_{\text{eff}}(1 + C_{11}\kappa) - \left(\frac{1.84}{R}\right)^2 \quad (8)$$

The split frequencies in such a gyromagnetic resonator are therefore described by

$$\frac{\Delta(k_0)}{k_0} = \frac{\Delta\omega_0}{\omega_0} = C_{11}\kappa \quad (9)$$

Taking κ as 0.48 and C_{11} as 0.84 gives

$$\frac{\Delta\omega_0}{\omega_0} = 0.40 \quad (10)$$

This quantity may be compared with a value of 0.29 obtained experimentally from the two split frequencies.

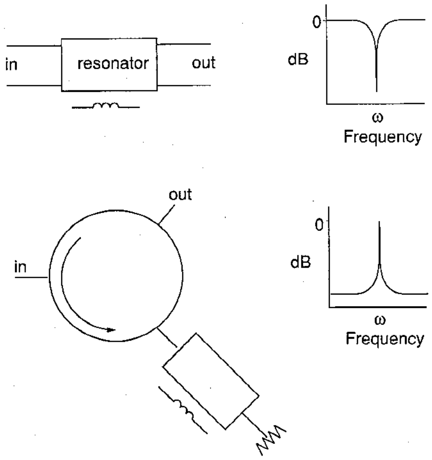

Fig. 16. Two-port bandstop and bandpass filters.

VII. Nonreciprocal 2-Port Bandpass Filters

Scrutiny of the frequency response of the 2-port circuit indicates that it may be used in the construction of a tunable reflective bandstop filter. It may also, in conjunction with a circulator, be used as a tunable bandpass filter with responses at both split frequencies. The schematic diagrams of these two arrangements are illustrated in Fig. 16. The gyromagnetic resonator is, in each instance, located at the plane of circular polarization in the rectangular waveguide.

VIII. 4-Port Tunable Filter

Some additional adjustments on a 4-port junction and some preliminary results on one assembly are described in this section. The relationship between the insertion loss and the size of the coupling aperture at the midband frequency and at frequencies on either side displaced from it by 500 MHz is illustrated in Fig. 17 for one arrangement. It applies to a junction using half-height rectangular waveguides with the axis of the apertures in the gyromagnetic resonator displaced by 6.0 mm from the middle of the waveguides. Fig. 18 depicts one typical response. The response at the lower frequency is obtained with an input at port 1 and that at the upper one with an input at port 4 in keeping with the equivalent circuits of the device in Figs. 2 and 3. The midband response is obtained with either an input at port 1 or 4. A feature of this result is the significant variation of the insertion loss of the device with frequency. One possible explanation for this situation is that the immittance of the split modes as well as the phase constants of the cavity are split by the gyromagnetic effect. The influence of the impedance level of the rectangular waveguides in the coupling region on the insertion loss of the device awaits a separate study. Scrutiny of the data in Fig. 12 indicates, however, that an impedance lower than that associated with half-height waveguide would have some merit. Figure 19 illustrates the detailed frequency responses of the scattering variables for the same cavity tuned about 1 GHz below the midband frequency. The insertion loss between the coupled

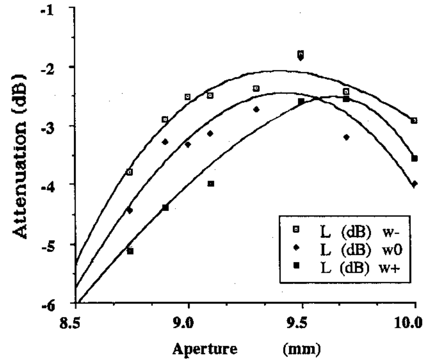

Fig. 17. Relationship between insertion loss at ω_-, ω_0 and ω_+ and aperture size.

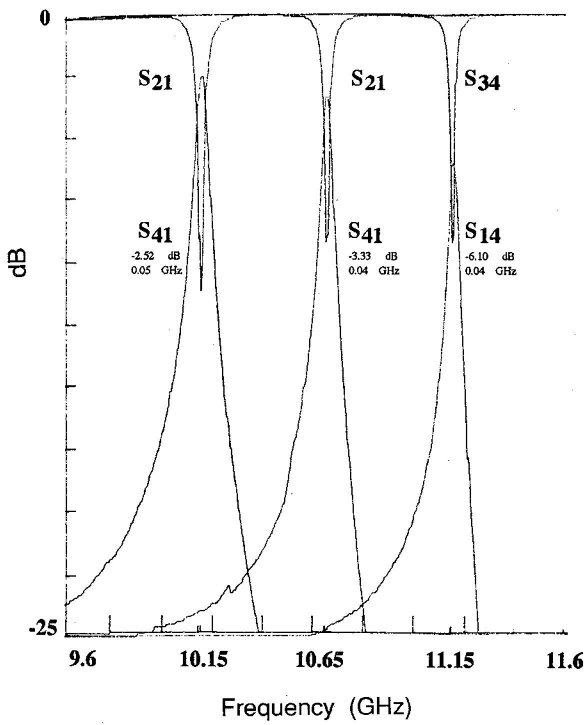

Fig. 18. Frequency response of four-port filter at ω_-, ω_0 and $\omega_+ (x = 6.0\ \mathrm{mm}, D = 9.5\ \mathrm{mm})$.

ports is below 1 dB at this frequency and the attenuation between the decoupled ones is typically 17 dB. The 3-dB bandwidth is 63 MHz. The insertion loss at this frequency is in keeping with the slope of this quantity displayed by the frequency response in Fig. 18. The precise result is

$$f_0 = 9.57\ \mathrm{GHz}$$
$$\mathrm{B.W.}\,(3\ \mathrm{dB}) = 63\ \mathrm{MHz}$$
$$S_{11} \approx 20\ \mathrm{dB}$$
$$S_{21} \approx 18\ \mathrm{dB}$$
$$S_{31} \approx 17\ \mathrm{dB}$$
$$S_{41} \approx 0.85\ \mathrm{dB}$$

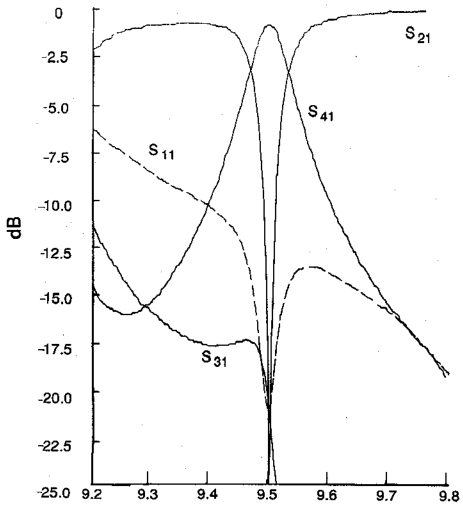

Fig. 19. Typical scattering parameters of nonreciprocal directional filter using magnetized gyromagnetic resonator ($\varepsilon_d = 2.56, k \approx 0.80, \varepsilon_f = 15.1$, $M_0 = 0.1600$ T, $R_i/L_i = 1.283$).

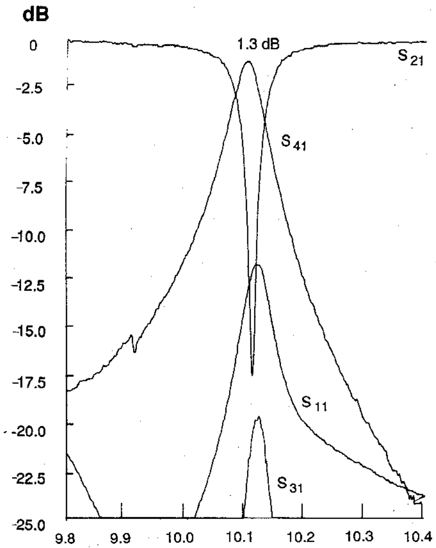

Fig. 20. Typical scattering parameters of nonreciprocal directional filter using demagnetized gyromagnetic resonator ($\varepsilon_d = 2.56, k \approx 0.77, \varepsilon_f = 15.1, M_0 = 0.1600$ T, $R_i/L_i = 1.127, R_i = 3.72$ mm).

The physical parameters of the gyromagnetic resonator utilized in obtaining this result are

$$\frac{R_i}{L_i} = 1.283$$
$$\frac{R_0}{L_0} = 1.84$$
$$\frac{\varepsilon_f}{\varepsilon_d} = 5.90$$
$$k \approx 0.80$$

and $R_i = 3.72$ mm, $R_0 = 7.0$ mm, $\varepsilon_f = 15.1$.

Figure 20 depicts some results on a reciprocal directional filter based on the material in [9] for comparison.

A quantity that has some influence on the insertion loss of the directional filter is its unloaded Q-factor (Q_u). Its value is dependent upon the fabrication of the cavity, the type of plating (if any), the effective linewidth of the garnet material, and the dielectric losses of the garnet and dielectric. No attempt has been made to optimize any of these quantities. Furthermore, no mention has been made about the spinwave linewidth of the material employed in this work. Its value is usually determined by the onset of spinwave instability or nonlinear effects in ferrites. The material employed in this work represents a compromise between the separate requirements of average and peak power ratings of the filter. Its peak power rating has, however, not been established.

IX. Conclusions

A half-wave long gyromagnetic resonator with open walls in a cylindrical metal enclosure has been utilized in this paper in the construction of a 4-port nonreciprocal tunable directional filter. The possibilities of constructing 2-port bandstop and bandpass filters using the same cavity have also been noted. The development of a conventional directional filter using a dielectric resonator may also have some promise. While the tuning range of the original specification of the device has been fully investigated, some additional attention to the impedance level of the coupling structure is still necessary.

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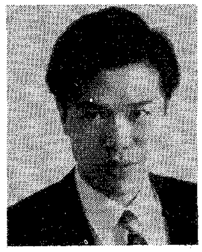

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