Properties of a Four-Port Nonreciprocal Circuit Utilizing YIG on Stripline—Filter and Circulator

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***Abstract*—Experimental results of the 4-port *nonreciprocal bandstop-pass filter* and the *tunable resonance type circulator* with the properties of the 4-port filter are reported, and the theory of the new nonreciprocal circuit is discussed.**

The filter operates over a *two-octave* frequency range and the circulator over about a *one-octave* frequency range.

Introduction

IN Polder's analysis [1] of the gyromagnetic resonance phenomenon, he pointed out, 1949, that ferromagnetic substances should show appreciable Faraday rotation at microwave frequencies. Hogan [2], [3] extended the study of Polder, discovered that ferrites should show considerable Faraday effects, and, moreover, showed that it could be used to make a microwave nonreciprocal element. Stimulated by this study of Hogan, many results on nonreciprocal microwave ferrite devices have been reported. Recently, numerous papers concerning YIG filters have been reported with the development of microwave integrated circuits.

In the case of striplines, however, most of the studies are on reciprocal filters, with only a few on nonreciprocal ones. Besides, in the case of nonreciprocal filters the reported bandwidth is narrow; the bandwidth of YIG nonreciprocal filters either utilizing striplines or applying slotlines is about 1.3:1 [4], [5]. This is due to the fact that it is difficult to obtain the required circularly polarized magnetic field over a wide bandwidth, especially when the circuit is composed of striplines.

In order to obtain a circularly polarized magnetic field we make two RF magnetic fields, with 90° phase difference, cross at right angles in space. In this study, to widen the characteristic of a circularly polarized magnetic field, we first take notice that the directional coupler with coupled transmission lines maintains a phase difference of 90° between its two outputs over a wide bandwidth [6]. Secondly, we make the outputs, which are obtained from two output ports of a directional coupler, cross at right angles in space; we have made two types of orthogonal couplings: Y form and X form.

However, in the case of Y-form coupling, complete matching of the input port is, in principle, impossible because it constructs a 3-port filter. From this reason Y-form coupling (3-port filter) will be omitted. Our analysis of these nonreciprocal elements will be mainly carried out by means of a scattering matrix. This procedure has been attained as follows: first, the impedance matrix of an X-form orthogonal coupling is represented as a function of Polder's tensor elements by an equivalent current model; second, this impedance matrix is transformed into a scattering matrix. We will present a nonreciprocal filter that is constructed of a 3-dB directional coupler, an X-form orthogonal coupling, and a single YIG sphere.

The experimental filter operates over a wide bandwidth of about 4:1 (about two octaves) as a nonreciprocal band*stop* filter. Moreover, the isolated port of a directional coupler has, at the same time, properties such that it can be used as the output port of a nonreciprocal band*pass* filter, since we have a 4-port device.

Making use of the characteristic of this nonreciprocal band*stop–pass* filter, we have developed a 4-port frequency tunable circulator. This circulator operates over a wide bandwidth of about one octave. Some other circulators recently reported have a comparable bandwidth [7]. However, the circulator developed in this study is very simple; moreover, it will be able, in principle, to extend its bandwidth to multioctaves if the directional coupler is adequately designed.

Circuit Structural Elements

The 4-port nonreciprocal circuit, as shown in Fig. 1, consists of one or two directional couplers (D_1, D_2), an X-form orthogonal coupling (X) in order to obtain a circularly polarized magnetic field in microstriplines, and a single YIG sample placed in the center of the field.

Directional Coupler

It is well known that the coupled-transmission-line directional coupler keeps the phase difference between output port 1′ and output port 4′ at 90° as long as it operates as a directional coupler, when port 1 is the input port. That is, assuming that the matching condition is completely satisfied, when an input a_1 is applied at port 1, the coupled wave at port 4′, the straight-through wave at port 1′, and the wave at isolated port 4 are b_4', b_1', and b_4, respectively; they are given by [8]

$$b_4' = \frac{jk \sin\theta}{\sqrt{1-k^2}\cdot\cos\theta + j\sin\theta}\cdot a_1$$

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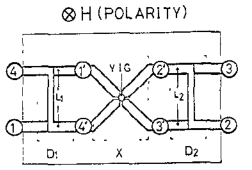

Fig. 1. Schematic 4-port circuit. D_1, D_2—directional couplers; X—orthogonal coupling.

$$b_1' = \frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\cdot\cos\theta + j\sin\theta}\cdot a_1$$
$$b_4 = 0, \qquad \text{for all frequencies} \tag{1}$$

where

θ electrical length of coupling region,
k coupling factor.

Therefore, by (1), the phase difference between output port 1′ and output port 4′ is given as follows:

$$\frac{b_4'}{b_1'} = j\frac{k}{\sqrt{1-k^2}}\cdot\sin\theta. \tag{2}$$

If, in (2), $\theta = 90°$ (a quarter wavelength) and $k = 1/\sqrt{2}$ (3-dB coupling), we get the following relation:

$$b_4' = jb_1'. \tag{3}$$

If a coupled-transmission-line directional coupler is adequately designed, (3) may be satisfied for a wide bandwidth [9]. Therefore, we can obtain a very widely circularly polarized magnetic field by making two outputs from the directional coupler cross at right angles in space. The scattering matrix of the directional coupler is given by

$$S_D = \begin{pmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & \beta \\ \beta & 0 & 0 & \alpha \\ 0 & \beta & \alpha & 0 \end{pmatrix} \tag{4}$$

where $\alpha = k$, $\beta = -j\sqrt{1-k^2}$.

X-Form Orthogonal Coupling

This study of the nonreciprocal circuit is based upon the characteristic of an X-form orthogonal coupling with a single YIG sphere.

An analysis of the orthogonal coupling utilizing guidewaves has been previously carried out by introducing the Q of the ferrite as a parameter, and an analysis of some special cases (wire loop coupling, wire semiloop coupling) also has been made [10], [11].

In this study we will investigate the characteristic of the orthogonal coupling by the scattering matrix and will summarize the results of the analysis. When a YIG sample is placed in the center of a circularly polarized magnetic field, the output response of each port is represented by the scattering matrix, that is, taking the symmetry of this circuit into account, the scattering matrix can be written as follows:

$$S_X = \begin{pmatrix} \Gamma & S_{12} & T & S_{21} \\ S_{21} & \Gamma & S_{12} & T \\ T & S_{21} & \Gamma & S_{12} \\ S_{12} & T & S_{21} & \Gamma \end{pmatrix} \tag{5}$$

where each element of S_X is in general described as a function of angular frequency (ω), external dc magnetic field (H), saturation magnetization $4\pi M_s$, and linewidth ΔH. But the last two are the intrinsic parameters of the material and once the material is selected, these two parameters are fixed. That is, $\Gamma = \Gamma(\omega, H)$, $T = T(\omega, H)$, $S_{12} = S_{12}(\omega, H)$, and $S_{21} = S_{21}(\omega, H)$.

If the geometric structure of an X-form coupling and the coupling strength of the YIG sphere are adequately designed, when the YIG sample is tuned to ferromagnetic resonance, it is possible to satisfy the following relations between these elements:

$$\Gamma_r - T_r \fallingdotseq 0 \tag{6a}$$
$$|S_{12}^r - S_{21}^r| \fallingdotseq 1 \tag{6b}$$
$$S_{21}^r = -S_{12}^r = \pm jT_r \tag{6c}$$

(sign + for $\otimes H_r$, sign − for $\odot H_r$) where index r means YIG resonance. Equation (6a) will be obtained through the assumption that an X-form coupling works perfectly when just half of the energy couples to the perpendicular arm. Equation (6c) comes from the fact that the positive circularly polarized magnetic field is necessary for YIG resonance and the (6b) will be easily obtained from the (6a) and (6c). This relation may be verified by experiments. The analysis in detail is omitted here [12]. Concerning the insertion losses of this circuit, the line loss and the loss due to YIG should be considered. Here no analysis has been done concerning these losses, but the insertion loss was measured experimentally.

Friedman [13] has investigated a slightly different circuit in a similar way. The difference in his circuit is the coupling part. He has used a parallel circuit technique. Here the coupling is straight through but is an X-form orthogonal coupling.

Circuit Structure

4-Port Filter

Fig. 2 shows one of the filters. This 4-port filter consists of a directional coupler, an X-form orthogonal coupling, and a single YIG sphere placed in the center of the circularly polarized magnetic field.

The unit input signal is applied at port 1 of the 4-port filter.

1) *When H is Zero:* As the YIG sphere, in this case, is regarded as only a dielectric, if the orthogonal coupling is sufficiently weak, we get $\Gamma(\omega, 0) = 0$, $T(\omega, 0) = 1$, $S_{12}(\omega, 0) = 0$, and $S_{21}(\omega, 0) = 0$. Therefore, the following

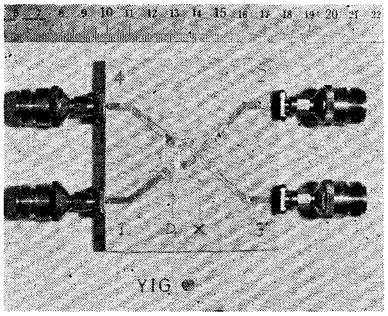

Fig. 2. 4-port filter.

results can be obtained:

$$\begin{aligned} &\text{port } 1: \; b_1 = 0 \qquad \text{(input port)} \\ &\text{port } 2': \; b_2' = \alpha \\ &\text{port } 3': \; b_3' = \beta \\ &\text{port } 4: \; b_4 = 0 \qquad \text{(isolated port)} \end{aligned} \tag{7}$$

where b_1, b_2', b_3', and b_4 are the output responses at port 1, 2′, 3′, and 4, respectively. Equation (7) can be considered to hold also for the case where the dc magnetic field is sufficiently far from the region of the field H_r required for YIG sphere resonance.

2) *When H is Equal to H_r (Polarity $\odot$):* A dc magnetic field H is then applied in perpendicular to the plane of an RF circularly polarized field. As the dc field H approaches H_r for YIG sphere resonance, the X-form coupling becomes sufficiently strong. Then the power absorbed in the YIG sphere is given by

$$P_0 = \mu_0 \omega_m Qu Vf(1+e) \,|\, h \,|^2 \tag{8}$$

where

- μ_0 vacuum permeability,
- ω_m $\gamma 4\pi M_s$ (γ = gyromagnetic ratio),
- $4\pi M_s$ saturation magnetization,
- Qu unloaded Q of the YIG sample,
- Vf volume of the YIG sample,
- e ellipticity of the normal modes of the uniform precession,
- h external driving RF magnetic field.

At the same time the relative permeability of the ferrite is given by

$$\mu_+ = 1 - j2 \cdot \frac{\omega_m}{\omega} \cdot Qu \tag{9}$$

where μ_+ is the relative permeability for the positive circularly polarized wave. The absolute value of μ_+ is then very large. It may be considered that the reason the output appears at port 4, as shown in (12), is that the permeability of the YIG sphere changes by a very large value at its resonance, so that the impedance level at the point of the X-form coupling also does and large reflections take place [2], [3]. Therefore, from (4) and (5), the output response at ports 2′ and 3′ can be written as follows:

$$\text{port } 2': \; b_2' = (S_{21}'\beta + T_r\alpha) \fallingdotseq 0 \tag{10a}$$

$$\text{port } 3': \; b_3' = (T_r\beta + S_{12}'\alpha) \fallingdotseq 0. \tag{10b}$$

Equations (10a) and (10b) state the condition that ports 2′ and 3′ have the characteristic of the band*stop* filter. Assuming that such a condition is satisfied, the output response of ports 1 and 4 are given by, respectively,

$$\text{port } 1: \; b_1 = (\alpha^2 + \beta^2)(\Gamma_r - T_r) \tag{11a}$$

$$\text{port } 4: \; b_4 = -\left(\frac{\beta^3}{\alpha} + \frac{\alpha^3}{\beta}\right) T_r + 2\alpha\beta\Gamma_r. \tag{11b}$$

Consequently, the matching condition of the input port is $\Gamma - T = 0$ or $\alpha^2 + \beta^2 = 0$. It is, in principle, difficult to satisfy widely the condition $\Gamma - T = 0$, because both Γ and T are considered to be functions of ω and H. On the other hand, it is possible to satisfy widely the condition $\alpha^2 + \beta^2 = 0$, by utilizing a 3-dB directional coupler (namely $\alpha = j\beta = 1/\sqrt{2}$). As long as the conditions mentioned above are satisfied the following results can be necessarily obtained:

$$\begin{aligned} &\text{port } 1': \; b_1 = 0 \qquad \text{(input port)} \\ &\text{port } 2': \; b_2' = 0 \\ &\text{port } 3': \; b_3' = 0 \\ &\text{port } 4: \; b_4 = -j(\Gamma_r + T_r). \end{aligned} \tag{12}$$

Equation (12) shows that the isolated port 4 of the directional coupler should be utilized as an output port of a nonreciprocal band*pass* filter. Moreover, it will be understood by simple calculation that (6) holds explicitly true.

Summing up the analytical results, in the case $H = H_r$ (polarity $\odot$) the behavior of this 4-port filter can be represented as follows:

$$\begin{pmatrix} b_1 \\ b_2' \\ b_3' \\ b_4 \end{pmatrix} = \begin{pmatrix} 0 & 2\alpha T_r & 2\beta T_r & -j(\Gamma_r - T_r) \\ 0 & \Gamma_r & jT_r & 2\beta T_r \\ 0 & -jT_r & \Gamma_r & 2\alpha T_r \\ -j(\Gamma_r + T_r) & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2' \\ a_3' \\ a_4 \end{pmatrix} \tag{13}$$

where the expression a_1, a_2', a_3', and a_4 denote the input signal at port 1, 2′, 3′, and 4, respectively.

In the case of making use of port 2′ (or port 3′) as an output port of the bandstop filter, at least 3-dB insertion loss cannot be avoided, due to the nature of this circuit. However, this insertion loss will be eliminated by means of adding another coupler D_2 to this filter, that is, if the coupling k_2 is 3 dB, port 2 is an output port and port 3 is an isolated port, as is discussed later.

4-Port Circulator

We have found it possible that the 4-port nonreciprocal bandstop–pass filter can be constructed of a direc-

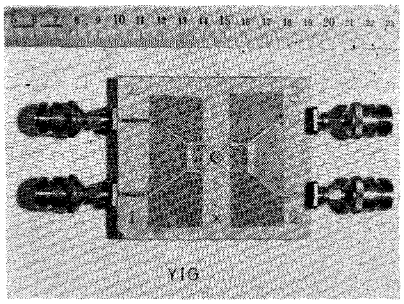

Fig. 3. 4-port circulator.

tional coupler and an X-form coupling with a single YIG sphere. The realization of a new circulator will be possible by making use of the properties mentioned above. Another coupler D_2 may be added to the filter as in Fig. 1. Fig. 3 shows one of the trial 4-port circulators. Here we will show what conditions are necessary to make a new 4-port circuit operate as a circulator.

1) *When H is Zero:* When an unit input signal is applied only at port 2, the output response at each port can be written as follows:

$$\begin{aligned} &\text{port 1: } b_1 = -j(k_1\sqrt{1-k_2^2} + k_2\sqrt{1-k_1^2}) \\ &\text{port 2: } b_2 = 0 \qquad \text{(input port)} \\ &\text{port 3: } b_3 = 0 \qquad \text{(isolated port of } D_2\text{)} \\ &\text{port 4: } b_4 = k_1k_2 - \sqrt{1-k_1^2}\cdot\sqrt{1-k_2^2} \end{aligned} \tag{14}$$

where

k_1 coupling factor of D_1,
k_2 coupling factor of D_2.

Two isolated ports should be required in order to make this 4-port circuit operate as a circulator. Therefore, from the necessary condition $b_4=0$, we get

$$k_1^2 + k_2^2 = 1. \tag{15}$$

When (15) is satisfied, the output at port 1 becomes $-j$. It means that the whole input signal applied at port 2 should appear at port 1.

Consequently, the scattering matrix expression is given as follows:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & -j & 0 & 0 \\ -j & 0 & 0 & 0 \\ 0 & 0 & 0 & -j \\ 0 & 0 & -j & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}. \tag{16}$$

Equation (16) approximately holds for the case where the dc magnetic field H is far enough from the YIG resonance field H_r. In this case, the four ports are divided in two pairs by a symmetrical line S–S' as shown in Fig. 4(a).

2) *When H is Equal to H_r (Polarity $\otimes$):* It has been discussed that large reflections take place at the point

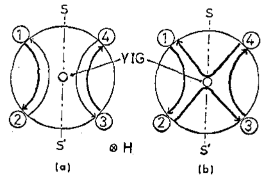

Fig. 4. Path model of 4-port circulator. H_r—field for YIG resonance. (a) H is far from H_r. (b) H is equal to H_r.

of the X-form coupling when H is equal to H_r. Under (15) and (6) the output response at each port can be written as follows:

$$\begin{aligned} &\text{port 1: } b_1 = j(2k_1k_2 - 1)T_r \\ &\text{port 2: } b_2 = -(k_1^2 - k_2^2)\Gamma_r \\ &\text{port 3: } b_3 = -j(2k_1k_2\Gamma_r + T_r) \\ &\text{port 4: } b_4 = -(k_1^2 - k_2^2)T_r. \end{aligned} \tag{17}$$

Therefore, from the requirement for perfect matching at port 2 or for perfect isolation at port 4, we get the condition $k_1 = k_2 = 1/\sqrt{2}$. Then (17) becomes

$$\begin{aligned} &\text{port 1: } b_1 = 0 \\ &\text{port 2: } b_2 = 0 \\ &\text{port 3: } b_3 = -j(\Gamma_r + T_r) \\ &\text{port 4: } b_4 = 0. \end{aligned} \tag{18}$$

Let us first consider when port 1 is an input port. As mentioned above, only port 2 becomes an output port. Second, when port 2 is the input port, then port 4 is an isolated port. The output of port 1 is zero because of the nonreciprocity of this circuit, that is, this circuit works as a bandstop filter in this direction. The output port appears at port 3 because of bandpass characteristics, as shown in Fig. 4(b).

Consequently, the behavior of this 4-port circuit can be expressed as follows:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -j(\Gamma_r+T_r) \\ -j2T_r & 0 & -j(\Gamma_r-T_r) & 0 \\ 0 & -j(\Gamma_r+T_r) & 0 & 0 \\ -j(\Gamma_r-T_r) & 0 & -j2T_r & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}. \tag{19}$$

In particular, when $T_r \fallingdotseq \Gamma_r$ and $T_r \fallingdotseq 1/2$, (19) becomes the simple form (20), approximately:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -j \\ -j & 0 & 0 & 0 \\ 0 & -j & 0 & 0 \\ 0 & 0 & -j & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}. \tag{20}$$

This equation shows nothing but the property of a 4-port circulator. The operational bandwidth of the 4-port circulator depends on the characteristic of the directional couplers D_1 and D_2. Since the frequency

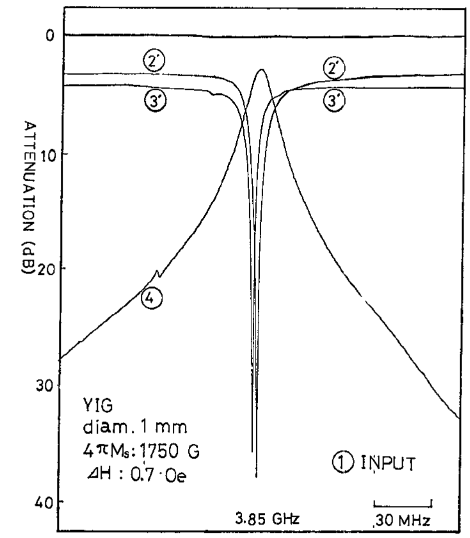

Fig. 5. Output response of the 4-port nonreciprocal filter. A dc magnetic field is fixed.

characteristic of the coupler, as just mentioned, is very wide, it is, in principle, able to make a wide bandwidth tunable circulator.

Experimental Results

Filter

As shown in Fig. 5 the 4-port filter has a bandstop filter (BSF) characteristic at port $2'$ and at port $3'$, but at the same time a bandpass filter (BPF) characteristic at port 4. Its insertion loss (off resonance) as a BSF at ports $2'$ and $3'$ is 3.2 dB and 4.3 dB, respectively. This difference between experimental results and theoretical insertion loss (3 dB) is due to the departure of the coupler from its 3-dB coupling factor. Its insertion loss (on resonance) as a BPF is 2.8 dB, but can be improved by utilizing a high-Q YIG sphere.

Fig. 6 shows that the filter operates for a two-octave frequency range as a bandstop filter: 2–6.8 GHz, if the isolation is more than 20 dB; 2–8 GHz, if the isolation is more than 15 dB and the insertion loss (off resonance) is 3–5 dB, which can be eliminated by means of the added 3-dB coupler D_2 (namely the insertion loss has been decreased to about 1 dB as in Fig. 7); the input VSWR (off resonance) is less than 1.6 (2–8 GHz). The performance of the bandpass filter is not as wide as that of the BSF, which is 2–6 GHz.

Circulator

This 4-port circuit works as a frequency tunable circulator, whose characteristic is shown in Fig. 7. That is: 1) when port 1 is the input port, the output appears at only port 2 because of the nonreciprocity of the circuit [both port 3 and port 4 are isolated ports as shown in (19)]; 2) when port 2 is the input port, the output response comes out only at port 3 because of the BPF characteristic of this circuit, but not at port 1 because of the nonreciprocity (that is, this circuit works as a bandstop filter in this direction). Port 4 is the isolated

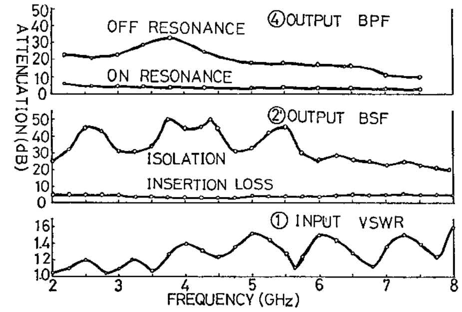

Fig. 6. Characteristic of the 4-port nonreciprocal filter, as a dc magnetic field is tuned to the YIG sphere resonance. Port 1—off resonance VSWR; port $2'$—insertion loss is the off resonance performance. The output at port $3'$ has performance similar to the output at port $2'$. Port 4—insertion loss is the output of a BPF on resonance. Isolation is the off resonance attenuation of a BPF.

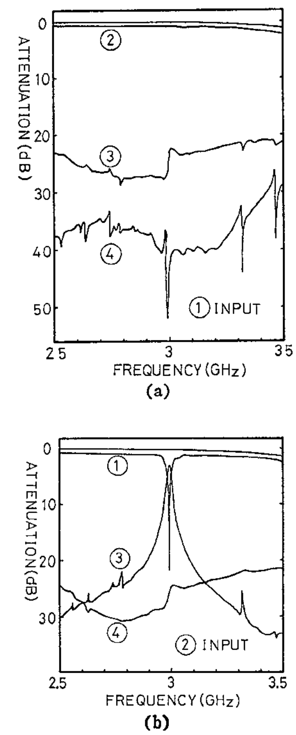

Fig. 7. Output response of the 4-port circulator. A dc magnetic field is tuned to the YIG sphere resonance at 3 GHz and fixed in (a) and (b).

TABLE I
OUTPUT RESPONSE (FIXED FIELD RESULT)

Output Port / Input Port	1	2	3	4
1	VSWR 1.28^a	-1 dB -1^a dB	-23 dB -23^a dB	-36 dB -37^a dB
2	-22 dB -1^a dB	VSWR 1.38^a	-3 dB -27^a dB	-24 dB -23^a dB

[a] Off resonance performance.

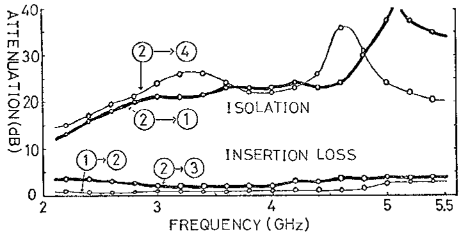

Fig. 8. Characteristic of the 4-port circulator, as a dc magnetic field is tuned across the frequency band. From port 1 to port 3: isolated port of this circuit, whose performance is similar to that of isolation from port 2 to port 4. From port 1 to port 4: isolated port of D_1, whose isolation is more than 18 dB (2–4 GHz) and more than 14 dB (2–5 GHz).

port for this case. These properties are summarized in Table I.

One will recognize by the experimental results that the required conditions mentioned previously, $\Gamma_r - T_r = 0$ and $T_r = \frac{1}{2}$, hold approximately true.

The tunable bandwidth of this circulator is about one octave, because the 3-dB couplers here are only single element and their available bandwidth is about one octave. Fig. 8 shows the characteristics of this 4-port circulator:

Nonreciprocity (from port 1 to port 2)
  insertion loss less than 1.5 dB (2–4.8 GHz).

BSF (from port 2 to port 1)
  isolation more than 20 dB (2.8–6 GHz) and more than 15 dB (2.4–6.8 GHz).

BPF (from port 2 to port 3)
  insertion loss less than 4 dB (2–5.5 GHz).

Isolated port (from port 2 to port 4)
  isolation more than 20 dB (2.6–6 GHz) and more than 15 dB (2.2–6 GHz).

VSWR (off resonance) less than 2.5 (2–6 GHz).

In principle, the wider the bandwidth of the couplers is designed, the wider the tunable bandwidth of the circulator can be. This circulator is very simple but its characteristic is quite good.

Conclusion

It has been found that the nonreciprocal bandstop–pass filter can be obtained by utilizing two directional couplers and an X-form coupling with a single YIG and, moreover, that the 4-port frequency tunable circulator also can be obtained. Their tunable frequency range is extremely wide compared with former ones and their structure is very simple.

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