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New Edge-Guided Mode Isolator Using Ferromagnetic Resonance Absorption

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***Abstract*—A new edge-guided (EG) mode isolator is described in which nonreciprocal attenuation is due to the ferromagnetic resonance absorption caused by a strong dc magnetic field applied locally at the short-circuited edge of a ferrite microstrip line.**

From modal analysis, including the magnetic losses of ferrite substrate and the transversal variation of the internal dc magnetic field, the dominant EG mode has been proved to propagate along not only the conventional ferrite stripline but also a stripline with one edge short circuited to the ground. Dispersion relations and RF electric field distribution have been calculated numerically, and the upper limit of isolator bandwidth has been discussed with several design parameters. Based on the results, a practical EG mode resonance isolator has been successfully developed, which has more than 25 dB isolation loss and less than 1.0 dB insertion loss over a 4.0–8.0-GHz frequency band throughout the −10°C–+60°C temperature range.

I. Introduction

The edge-guided (EG) mode isolator, utilizing the nonreciprocal field displacement effect in a ferrite stripline, was first investigated by Hines [1]. He constructed an isolator in which the resistive element is loaded asymmetrically on one side of the ferrite microstrip line. The isolator has very wide-band characteristics and an advantageous adaptability to MIC's. Since then, several authors have discussed the EG mode devices [2], [3]. Courtois *et al.* have used an unsaturated portion of the ferrite substrate as a reverse-wave absorber [4].

Lately, Araki *et al.* [5], [6] presented an EG mode isolator in which an edge of the ferrite microstrip is short circuited to the ground. It has a simple structure without lossy materials, a large isolation of about 60 dB, and the bandwidth of about 1–2 GHz. The operation of this isolator has been explained, via mode transformation theory, at the shorted edge discontinuity.

A new EG mode isolator was reported that used ferromagnetic resonance absorption in ferrite substrate [7]. A dc magnetic field is applied almost uniformly on the ferrite substrate by an electromagnet and is strengthened locally by a thin iron plate placed parallel to the dc field just above an edge of the strip conductor. A forward wave travels without attenuation along the edge where the field is weak. However, a backward wave, which travels along another edge where the field is strong, suffers an attenuation due to the ferromagnetic resonance absorption. The isolator performance is shown with solid lines A in Fig. 1. A fairly wide-band characteristic over 4–7 GHz is obtained.

Another simple method for obtaining an inhomogeneous internal dc field was also described [7]. This method used a disuniform demagnetizing field at the edge of the ferrite substrate with uniform field application. Even if a uniform field is applied, the internal dc magnetic field increases steeply at the edge of the ferrite substrate, because of the spontaneously induced disuniform demagnetizing field [8]. In fact, it has been proved experimentally [7] that nonreciprocal transmission losses are obtained when the center conductor has gotten near to the edge of the ferrite.

In further experiments [9], a strong local field was applied along short-circuited edge of the stripline which was proposed by Araki *et al.*, as shown in Fig. 2. In this case, the center conductor will be called a short–open boundary

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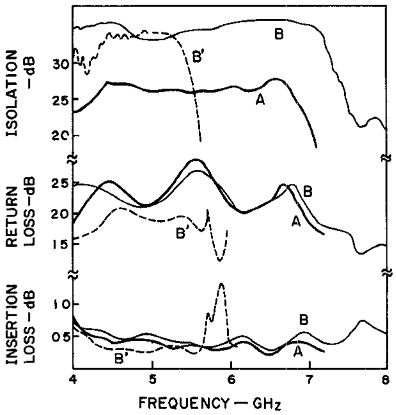

Fig. 1. Performances of EG mode ferromagnetic resonance isolators. A: Open–open type. B: Short–open type. B′: Short–open type without the iron plate.

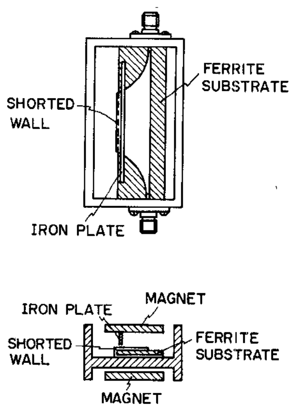

Fig. 2. Experimental EG mode isolator setup with use of the short-circuited stripline.

stripline, while a conventional center conductor will be called an open–open-type stripline. Even in the short–open stripline case, similar EG mode resonance isolator performance can be obtained, as shown with solid lines B in Fig. 1. Dotted lines B′ indicate isolator performance without iron plate for focusing dc magnetic field. The bandwidth is expanded remarkably by strengthening the local dc magnetic field with iron plate.

This paper describes these new types of EG mode isolator, in which nonreciprocal attenuation is obtained from the ferromagnetic resonance absorption [10].

Dominant forward and backward EG modes, which show nonreciprocal resonance attenuation, have been studied theoretically via modal analysis, including ferrite losses and the transversal variation of the internal dc magnetic field. A practical EG mode resonance isolator has been developed which has an isolation loss greater than 25 dB and an insertion loss less than 1.0 dB over 4–8-GHz frequency band.

II. EG Mode Analysis in Resonance Isolator

In conventional EG mode analyses, the internal dc magnetic field has been assumed to be uniform [1], [2], [11].

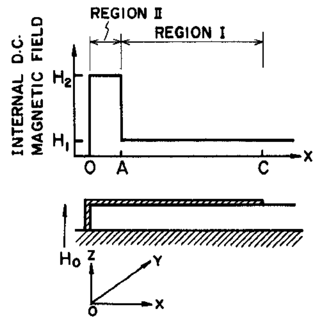

Fig. 3. Internal field model and coordinates system for analyses.

Fig. 3 shows the internal field assumed here. The area under the line conductor is divided transversely into two regions where the internal field is uniform. A more realistic field variation can be obtained by increasing the number of regions. The simplest case, with only two regions, is treated in this section. Characteristics of the EG mode, propagating along a disuniformly magnetized stripline, may be understood considering the simplest case of a stepwise uniform internal dc field. In this analysis, both the open–open stripline and the short–open type are treated. To simplify the analysis, it is also assumed that the boundary plane on the stripline edge is the magnetic wall at the open side and the electric wall at the shorted side.

A. Characteristic Equation

Rectangular coordinates are fixed to the stripline (Fig. 3). C is the width of the strip conductor and A is the width of region II, strongly magnetized compared with region I. The dc magnetic field is applied in the positive Z direction. In this case, the permeability tensor is written as follows:

$$\boldsymbol{\mu} \equiv \begin{bmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{bmatrix} = \begin{bmatrix} \mu & -j\kappa \\ j\kappa & \mu \end{bmatrix}. \tag{1}$$

The magnetic losses of the ferrite substrate are taken into consideration using a complex permeability. This treatment makes it possible to evaluate the isolation factor and the attenuation constants of waves propagating along the stripline. The circular polarization permeabilities are related to diagonal and off-diagonal elements of the permeability aforementioned tensor. They are written as follows:

$$\mu_{\pm} = \frac{\mu \mp \kappa}{2} = 1 + \frac{\omega_m}{\omega_r \mp \omega + j\gamma \cdot \Delta H/2},$$
$$\omega_m = \gamma \cdot 4\pi Ms \tag{2}$$

where γ is the gyromagnetic ratio, $4\pi Ms$ is the saturation magnetization, ω_m is the saturation magnetization frequency, ω_r is the ferromagnetic resonance frequency, and ΔH is the ferromagnetic resonance linewidth.

The substrate is sufficiently thin, compared with the wavelength, so that the RF field components are Z-independent quantities. In this case, TE modes with field components E_z, H_x, and H_y propagate. When the time-dependent part is expressed in $\exp(j\omega t)$, the field components are written in the following differential equations [12]:

$$(\nabla_t^2 + \omega^2 \varepsilon_0 \varepsilon \mu_0 \mu_e) E_z = 0 \tag{3}$$

$$H_t = S \nabla_t E_z \tag{4}$$

provided that

$$\mu_e = \frac{\mu^2 - K^2}{\mu} \tag{5}$$

$$S = \frac{-j}{\omega \mu_0 \mu_e} \begin{bmatrix} j\kappa/\mu & -1 \\ 1 & j\kappa/\mu \end{bmatrix} \tag{6}$$

$$\nabla_t = \begin{bmatrix} \partial/\partial X \\ \partial/\partial Y \end{bmatrix}$$

$$H_t = \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

where ε_0 is the electric permittivity of free space, ε is the relative permittivity of the ferrite, and μ_0 is the magnetic permeability of free space.

1) *Short–Open Type:* For the short-open-type stripline, the following boundary condition, corresponding to the magnetic wall or the electric wall, is given at each side of the line:

$$E_{z2} = 0, \quad \text{at } X = 0 \tag{7}$$

$$H_{y1} = 0, \quad \text{at } X = C \tag{8}$$

where suffixes 1 and 2 indicate the field component in regions I and II, respectively. The other constants which belong to these regions will be also indicated by the suffix 1 and 2 in the following.

By solving the differential equations (3) and (4) subject to boundary conditions (7) and (8), the field components in regions I and II are derived as follows:

Region I:

$$\omega^2 \varepsilon_0 \varepsilon \mu_0 \mu_{e1} \equiv (\omega/V)^2 \mu_{e1} = K_y^2 + \kappa_{x1}^2 \tag{9}$$

$$E_{z1} = \frac{B_1}{K_{x1}} \left\{ K_{x1} \cos K_{x1}(C - X) + \frac{K_1}{\mu_1} \cdot K_y \sin K_{x1}(C - X) \right\} \cdot \exp(-jK_y Y) \tag{10}$$

$$H_{y1} = \frac{-jB_1}{\omega \mu_0 K_{x1}} \left\{ \left(\frac{\omega}{V}\right)^2 - \frac{1}{\mu_1} K_y^2 \right\} \cdot \sin K_{x1}(C - X) \cdot \exp(-jK_y Y) \tag{11}$$

$$H_{x1} = \frac{B_1}{\omega \mu_0 K_{x1}} \left\{ \frac{K_{x1} \cdot K_y}{\mu_1} \cos K_{x1}(C - X) + \frac{\kappa_1}{\mu_1} \cdot \left(\frac{\omega}{V}\right)^2 \sin K_{x1}(C - X) \right\} \exp(-jK_y Y). \tag{12}$$

Region II:

$$(\omega/V)^2 \mu_{e2} = K_y^2 + K_{x2}^2 \tag{13}$$

$$E_{z2} = B_2 \sin(K_{x2} \cdot X) \cdot \exp(-jK_y Y) \tag{14}$$

$$H_{y2} = \frac{B_2}{\omega \mu_0 \mu_{e2}} \cdot \left\{ K_{x2} \cos K_{x2} X + \frac{\kappa_2}{\mu_2} \cdot K_y \sin K_{x2} X \right\} \exp(-jK_y Y) \tag{15}$$

$$H_{x2} = \frac{B_2}{\omega \mu_0 \mu_{e2}} \cdot \left\{ \frac{\kappa_2}{\mu_2} \cdot K_{x2} \cos K_{x2} X + K_y \sin K_{x2} X \right\} \exp(-jK_y Y) \tag{16}$$

where K_x, K_y, and V are X and Y components of the propagation constant and the light velocity in the dielectric substance with an ε equal to that of ferrite.

On the boundary plane between regions I and II, that is, at $X = A$ in these coordinates, the tangential component of region I and region II, that is, E_{z1}, H_{y1} and E_{z2}, H_{y2}, would be equalized, respectively. As a result, a set of two equations and therefore the secular determinant, is obtained. To simplify the equation, the following variables are introduced:

$$B = C - A \qquad W = \omega C/V$$

$$K = K_y C \qquad P_1 = K_{x1} B \qquad P_2 = K_{x2} A. \tag{17}$$

The secular equation is given by the new variables.

$$\left\{ \frac{C}{B} P_1 \frac{\cos P_1}{\sin P_1} + \frac{\kappa_1}{\mu_1} K \right\} \cdot \left\{ \frac{C}{A} P_2 \frac{\cos P_2}{\sin P_2} + \frac{\kappa_2}{\mu_2} K \right\} - \mu_{e2} \left(W^2 - \frac{1}{\mu_1} K^2 \right) = 0. \tag{18}$$

Every constant, other than one arbitrary constant, is determined from simultaneous equations (9), (13), and (18). Then the characteristics of the RF field components can be finally understood.

2) *Open–Open Type:* For the conventional (open–open-type) stripline, the following boundary conditions, corresponding to the magnetic wall, are given at both sides:

$$H_{y2} = 0, \quad \text{at } X = 0 \tag{19}$$

$$H_{y1} = 0, \quad \text{at } X = C.$$

The boundary condition in region I is the same as has been given in Section II-A1). Therefore, the field components are also expressed by (9)–(12). Under the boundary condition (19), the field components in region II are derived from (3) as follows:

Region II:

$$(\omega/V)^2\mu_{e2} = K_y^2 + K_{x2}^2$$

$$E_{z2} = \frac{B_2}{K_{x2}} \cdot \left\{K_{x2}\cos K_{x2}X - \frac{\kappa_2}{\mu_2}\cdot K_y \sin K_{x2}X\right\} \exp(-jK_yY) \quad (20)$$

$$H_{y2} = \frac{jB_2}{\omega\mu_0 K_{x2}} \left\{\left(\frac{\omega}{V}\right)^2 - \frac{1}{\mu_2} K_y^2\right\} \sin K_{x2}X \cdot \exp(-jK_yY) \quad (21)$$

$$H_{x2} = \frac{B_2}{\omega\mu_0 K_{x2}} \cdot \left\{\frac{K_{x2}K_y}{\mu_2}\cos K_{x2}X - \frac{\kappa_2}{\mu_2}\cdot\left(\frac{\omega}{V}\right)^2 \sin K_{x2}X\right\} \cdot \exp(-jK_yY). \quad (22)$$

The secular equation is obtained by use of the continuity condition to the tangential components of both regions on the boundary plane. The result is written as

$$\left\{\frac{C}{B}\cdot P_1 \frac{\cos P_1}{\sin P_1} + \frac{\kappa_1}{\mu_1} K\right\} \cdot \left\{W^2 - \frac{1}{\mu_2} K^2\right\} + \left\{\frac{C}{A}\cdot P_2 \frac{\cos P_2}{\sin P_2} - \frac{\kappa_2}{\mu_2} K\right\} \left\{W^2 - \frac{1}{\mu_1} K^2\right\} = 0. \quad (23)$$

B. Numerical Analysis

In order to analyze the EG mode propagation concretely, the simultaneous equations which comprise secular equations (18) or (23) and propagation constant equations (9) and (13) have been solved numerically, not algebraically. In these equations, propagation constants and magnetic material constants are treated as complex variables. Propagation constants of any mode are obtained on the complex plane with frequency as a parameter. Therefore, attenuation induced by magnetic loss can be determined from the imaginary part. Dielectric loss is excluded in this analysis.

Solutions of the secular equation are determined under the following convergent condition for magnitude of the left-hand side F of (18) and (23):

$$|F| < 10^{-3}.$$

Assuming a C-band isolator, typical values of the parameters are taken up for the computation. The substrate is YIG, whose saturation magnetization is 1800 G, the ferromagnetic resonance linewidth is 40 Oe and the relative permittivity is 14. The internal fields in regions I and II are zero and 1.44 kOe, respectively. C is 1.0 cm and A is 0.1 cm.

Figs. 4 and 5 show the dispersion relations of EG modes along the short–open and the open–open-type stripline, respectively. In these figures, solid lines refer to the wave numbers, namely, the real part of K, and broken lines

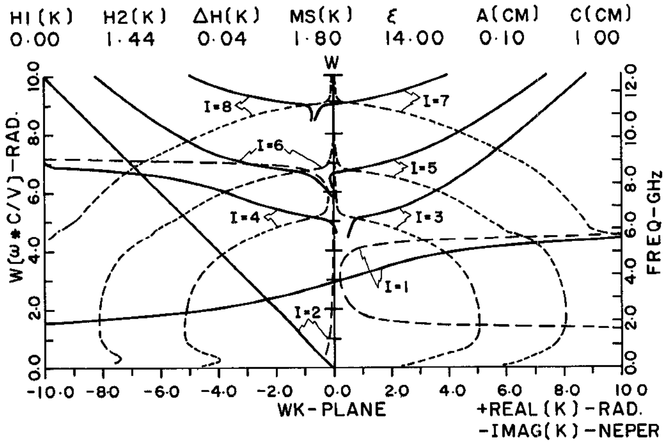

Fig. 4. Dispersion relations of several lower order modes along the short–open-type stripline.

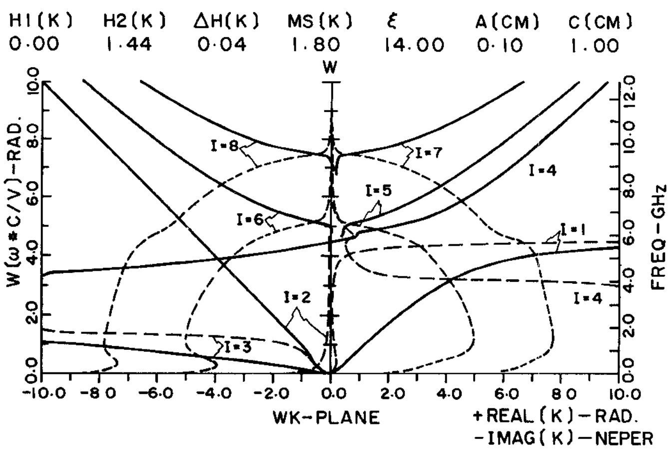

Fig. 5. Dispersion relations of several lower order modes along the open–open-type stripline.

refer to the attenuation constants, namely, the imaginary part of $(-)$ K. Then the mode I numbers are labeled to a pair of branches which express the characteristics of the same mode. The parts of solid lines which lie near the center axis are omitted in order to prevent the figure being jumbled up in disorder.

In Figs. 6 and 7, the transversal variation of amplitude of the RF electric field, normalized to its maximum values, is illustrated for each mode.

From these results, it was found that the electric field of the mode, $I = 1$, concentrates not at the edge, but at the interface between regions I and II and that this mode propagates in the $(+)$ Y direction with large attenuations at about a 6-GHz frequency. The field displacement of mode 1 becomes larger as the frequency becomes higher. This mode is the magnetostatic mode coupled with an electromagnetic mode.

On the other hand, the RF field of mode 2 concentrates at the edge of region I. Thus this mode can propagate with small attenuations over almost the full frequency range because there is little effect from region II and the shorted

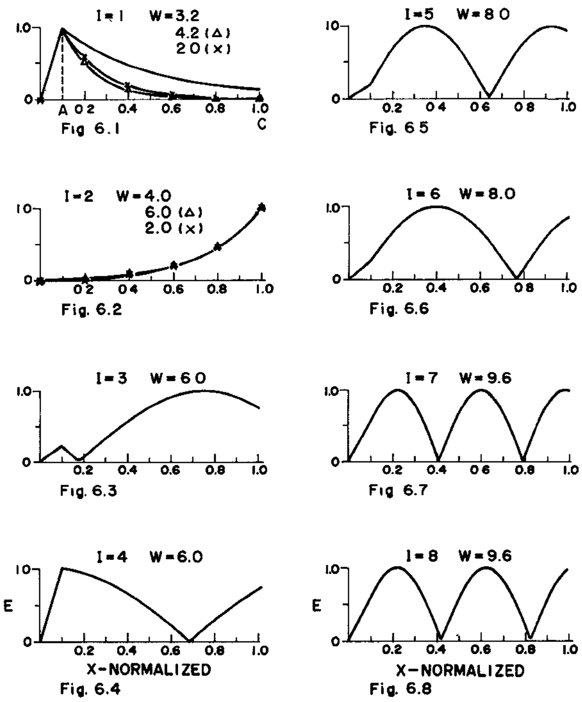

Fig. 6. Transversal RF field variations of each mode shown in Fig. 4.

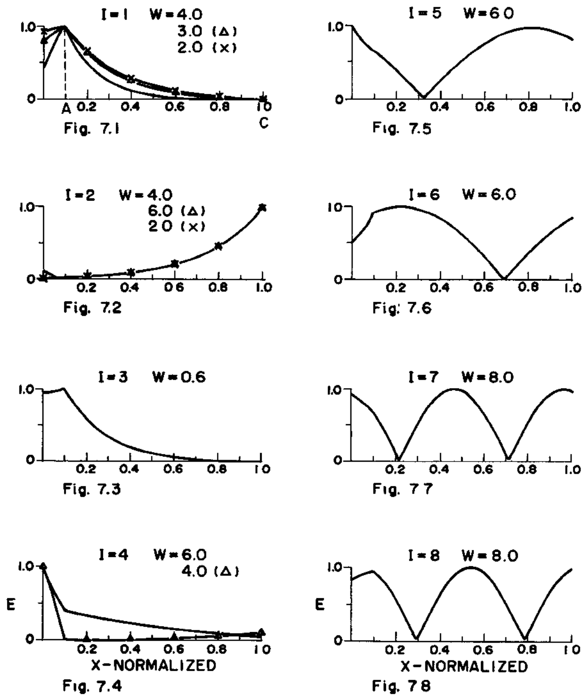

Fig. 7. Transversal RF field variations of each mode shown in Fig. 5.

side wall. The field displacement of this mode is independent of frequency. The fact results from the assumption that internal dc field $H_1 = 0$. This property of mode 2 closely corresponds to the EG mode analyses reported by Hines [1], not only for the open–open type but also for the short–open-type stripline.

From the aforementioned results, it is recognized that dominant modes which constitute the EG mode resonance isolator are modes 1 and 2.

Moreover, from these figures it is possible to obtain information for higher order modes (volume modes) whose field varies sinusoidally in the transverse plane, and the other magnetostatic modes, that is, mode 4 in Fig. 4 and modes 3 and 4 in Fig. 5.

III. Bandwidth Estimation

A. EG Mode Asymptotic Frequency

As shown in the dispersion relations in Figs. 4 and 5, the EG mode, which propagates in the (+) Y direction (mode 1), suffers large attenuation, approaching the asymptotic frequency of about 6 GHz. The asymptotic frequency implies the upper frequency limit at which a microwave signal obtains sufficiently large absorptive loss in the resonance isolator.

To simplify the analysis, it is assumed hereafter that ferrite substrate is free of losses. Provided that the normalized propagation constant K is sufficiently larger than the normalized angular frequency W, and (9) and (13) can be reduced to the following approximate equations, except at the frequency at which effective permeabilities μ_{e1} and μ_{e2} become infinite,

$$P_1C/KB \fallingdotseq \pm j \tag{24}$$

$$P_2C/KB \fallingdotseq \pm j. \tag{25}$$

1) *Short–Open Type:* Making absolute K sufficiently large after substituting (24) and (25) into (18), the approximate characteristic equations are obtained for $\pm K$ as follows:

$$\frac{\mu_{\mp 2}}{\mu_1 \cdot \mu_2}(\mu_{\mp 1} + \mu_{\pm 2}) = 0, \qquad (\pm K). \tag{26}$$

Substituting (2) wherein $\Delta H = 0$ into the parenthesized term of (26), the quadratic equation has been solved with respect to ω. For $\pm K$, the solutions, asymptotic angular frequencies, are given as

$$\omega = \sqrt{\frac{\omega_{r2} + \omega_{r1}}{2}\left(\frac{\omega_{r2} + \omega_{r1}}{2} + \omega_m\right)} \pm \frac{\omega_{r2} - \omega_{r1}}{2}, \qquad (\pm K) \tag{27}$$

where ω_{r1} and ω_{r2} are the ferromagnetic resonance frequencies of μ_+ in regions I and II, respectively.

It is obvious that, for $+K$ and $-K$, other solutions are obtained directly as

$$\mu_1 = \infty \quad \text{at} \quad \omega = \omega_{r1}, \qquad (+K) \tag{28}$$

provided, except that $\omega_{r1} = 0$, and

$$\mu_{+2} = 0 \quad \text{at} \quad \omega = \omega_{r2} + \omega_m, \qquad (-K). \tag{29}$$

These derived solutions correspond to asymptotic frequencies in Fig. 4, i.e., the frequencies given in (27) represent upper and lower asymptotic frequencies of EG mode 1 and the frequency given in (29) is the asymptotic frequency of first higher order mode 4. The solution of (28) is, however, not presented in Fig. 4 because of the assumption that $H_1 = 0$.

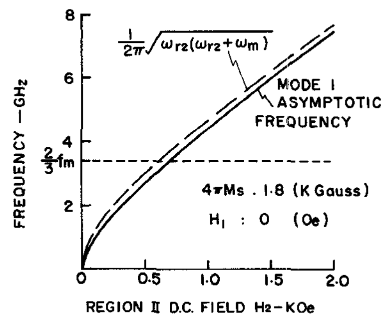

Fig. 8. EG mode asymptotic frequencies against the region II internal field.

2) *Open–Open Type:* As was reported in Section III-A1) for $\pm K$, the approximate characteristic equations are derived from (23) as follows:

$$\frac{1}{\mu_1 \cdot \mu_2} (\mu_{\mp 1} + \mu_{\pm 2}) = 0, \qquad (\pm K). \tag{30}$$

The terms in parentheses are the same as those parenthesized in (26). Therefore, (27) also gives the solutions of (30). Moreover, other solutions are

$$\mu_1 = \infty \quad \text{at} \quad \omega = \omega_{r1}, \qquad (+K) \tag{31}$$

provided, except where $\omega_{r1} = 0$, and

$$\mu_2 = \infty \quad \text{at} \quad \omega = \omega_{r2}, \qquad (-K) \tag{32}$$

provided, except where $\omega_{r2} = 0$.

These solutions, except (31), correspond to the asymptotic frequencies of modes 1, 3, and 4, respectively.

From the viewpoint of constructing resonance isolators, the most interesting asymptotic frequency is that of mode 1, which is the EG mode with $(+K)$. In Fig. 8, therefore, asymptotic frequencies in gigahertz are plotted against the internal field of region II in kilooersted with a solid line, calculating from (27). It is assumed that $H_1 = 0$ and $4\pi Ms = 1800$ G. The value of parameters is the same as in Figs. 4 and 5. In this figure, $\omega_{e2}/2\pi$, that is, the resonance frequency of effective permeability μ_{e2}, is also plotted with a broken line for comparison purposes.

$$\omega_{e2} = \sqrt{\omega_{r2}(\omega_{r2} + \omega_m)}. \tag{33}$$

Fig. 8 shows that the frequency range, where the EG mode 1 propagates, become wider in proportion to H_2. This implies that, in constructing the isolator, the upper limit of the frequency where large isolation can be taken may be raised to the asymptotic frequencies by increasing H_2, provided the higher order modes are suppressed.

B. Cutoff Frequencies

The cutoff frequencies of the first higher order modes, which are often troublesome for applications, have been computed from (18) and (23) for both the short–open and the open–open-type stripline. Results have been compared with each other.

In Fig. 9 the cutoff frequencies of the first higher order mode are shown versus the width of region I, B. The parameter values used are the same as those in Fig. 4.

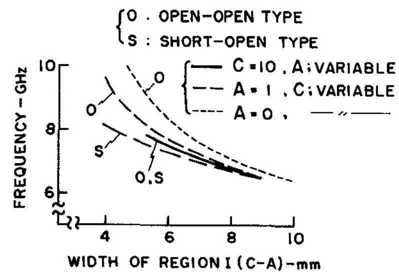

Fig. 9. Cutoff frequencies of the first higher order mode.

For raising the cutoff frequency of the higher order mode, it is effective to narrow the width of region I, C–A. The solid line represents the variation when C is fixed at 10 mm and the width of region II, A is varied. In this case, almost the same variations are seen for both short–open and open–open stripline. The broken lines, however, represent the variation when C is varied and A is fixed at 1 mm. Moreover, the cutoff frequencies in the uniformly magnetized open–open stripline are shown with the assumption of a magnetic wall at both sides.

From Fig. 9 better means are known to raise the cutoff frequency. It is effective for the open–open type to make the linewidth narrow, and for the short–open type to make region II wide. However, the width of region II must be narrow enough to prevent higher order modes from being excited in region II at a frequency region below magnetic resonance.

IV. EG Mode Resonance Isolator Characteristics

On the basis of the theoretical and experimental results presented hitherto, a practical EG mode resonance isolator has been successfully constructed. The short–open-type stripline has been used in the isolator because of its higher isolation, compared with the open–open-type stripline.

The EG mode isolator construction is the same as that shown in Fig. 2. The stripline is composed of three parts. One is the center portion of the short–open-type uniform line, which is 10 mm in width. The others are tapered lines, which match to the input and output lines to the wide stripline over a wide frequency band. The stripline conductor, the short-circuiting wall conductor, and the ground conductor are made of Cu thin film covered with plated Au film.

The soft iron plate (40 × 7 × 1 mm) is located near the short-circuiting wall to apply a strong magnetic dc field locally. This iron plate can be shifted in the transverse direction within a few millimeters to adjust the frequency dependence of isolation characteristics. Performance data of the isolator are shown in Fig. 10. The isolation is greater than 25 dB and insertion loss is less than 1.0 dB over the 4–8-GHz frequency range in the −10°C–+60°C temperature range. Input and output return loss is greater than 18 dB within the band.

The substrate (50 × 15 × 0.63 mm) is made of polycrystalline pure YIG. Saturation magnetization is 1780 G and the dielectric constant is 14. A uniform dc field of about

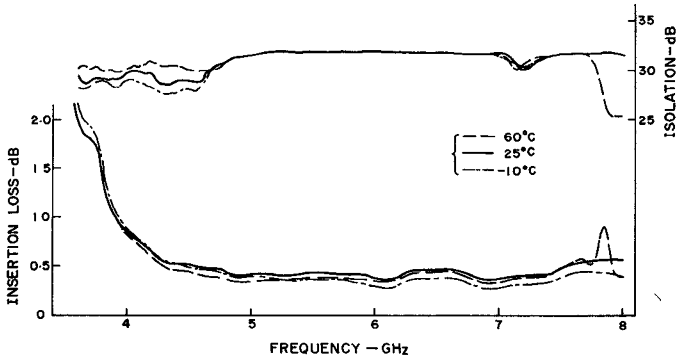

Fig. 10. 4–8-GHz frequency band EG mode resonance isolator performance throughout a −10°C–+60°C temperature range.

1800 Oe is applied by two pieces of SmCo ferrite magnets. The dc field, measured by a Hall-effect magnetometer just under the iron plate, is about 3900 Oe.

From these experimental results, it is found that higher order modes are suppressed up to 8 GHz by sliding the iron plate somewhat to the center portion and making the strong field region sufficiently wide. On the other hand, the locally applied field is strong enough to obtain isolation at 10 GHz, calculated from (27), with assumption of a demagnetizing field of $\frac{1}{2} \cdot 4\pi Ms$ at the edge of the substrate [9]. Thus, if it is intended to extent the frequency band to 10 GHz, a narrower stripline must be used for higher order mode suppression.

V. Conclusion

A new type of EG mode isolator, which makes use of ferromagnetic resonance absorption in the ferrite substrate, has been investigated theoretically and experimentally. From EG mode analysis, including ferrite substrate magnetic loss, the following results have been derived.

1) Provided that an internal dc magnetic field is strengthened locally, the EG modes can propagate in both forward and backward directions along not only the conventional ferrite stripline, but also the short–open stripline whose one side edge is short circuited to the ground.

2) Nonreciprocal attenuation of EG modes occurs owing to magnetic resonance absorption caused by the local dc magnetic field.

The numerical results have been shown in several diagrams of dispersion relations and RF electric field distributions, including dominant EG modes and higher order modes. In order to estimate the bandwidth of this isolator, the asymptotic frequency at which a microwave signal suffers sufficiently large absorption loss and cutoff frequency of higher order modes has also been computed approximately, as a function of a few design parameters such as local magnetic field strength and stripline width. On the basis of the results, a practical EG mode resonance isolator has been successfully developed.

Performances obtained are more than 25-dB isolation loss and less than 1.0-dB insertion loss over the 4–8-GHz frequency range in the −10°C–+60°C temperature range.

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