Normal Mode Nomenclature of Quadrupole Gyromagnetic Waveguides

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Abstract—**An important nonreciprocal rhombic or circular gyromagnetic waveguide used in the design of nonreciprocal quarter and half-wave plates is one with a quadrupole direct magnetic field. This paper reviews the normal mode nomenclature of this type of waveguide and gives a perturbation and anisotropic formulation of the normal modes of this type of waveguide which is in keeping with the existing literature. It also describes a closed-form formulation of the problem. The field distributions in this type of waveguide display a classic edge mode effect.**

I. Introduction

An important nonreciprocal birefringent gyromagnetic waveguide consists of a circular or rhombic waveguide transversely magnetized by a quadrupole direct magnetic field. One application of this type of waveguide is in the practical construction of nonreciprocal quarter-wave plates [1]–[10], [27]; another is in the construction of reciprocal ferrite phase shifters. Still another is in the fabrication of electronic rotable half-wave plates [13], [18], [19], [25], [27], [31], [33]. Some recent theoretical efforts are described in [20]–[22], [26], [29], and [30]. While the physical explanation for this class of device is historically available it has perhaps been taken for granted over the years. The nature of the normal modes of the quadrupole gyromagnetic waveguide is therefore carefully rehearsed as a preamble to the main endeavor of this work, which is the derivation of the field distributions in this type of waveguide using the phenomenological waveguide described in [16] and [19]. In the case of the rhombic gyromagnetic waveguide the symmetry of the problem indicates that one normal mode at the coupled ports establishes a dominant TE_{01} mode in square waveguide with one value of propagation constant, and that the other normal mode at the coupled ports establishes a TE_{10} mode in square waveguide with a different value of propagation constant. The normal modes are linear combinations of in-phase and out-of-phase in-space quadrature rhombic waveguide modes. An upper bound on the phase constants of the two normal modes is obtained by assuming that these coincide with the two possible states of a square gyromagnetic waveguide with its two halves magnetized in opposite directions. The anisotropic and perturbation formulations of its split phase constants in terms of an effective off-diagonal element of the tensor permeability are separately derived. The coupled mode description of this type of problem is also included for completeness.

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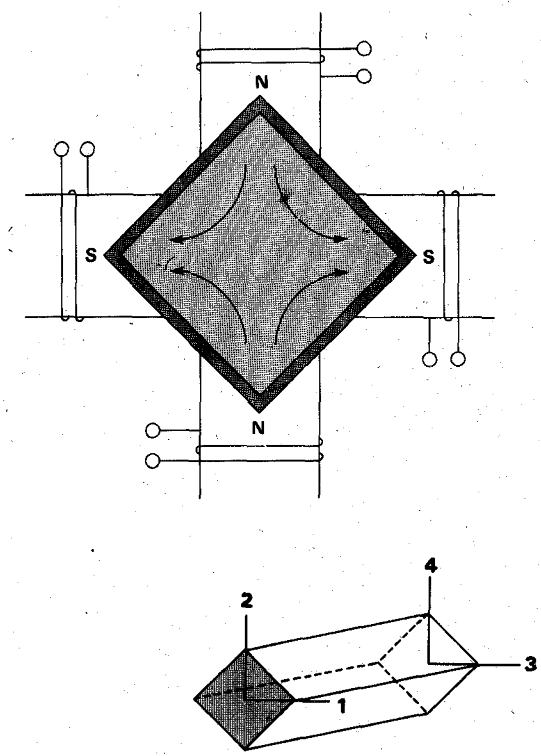


Fig. 1. Schematic diagram of quadrupole rhombic gyromagnetic waveguide.

II. Normal Modes of Quadrupole Field Gyromagnetic Waveguide

A circular or rhombic gyromagnetic waveguide may be described in terms of either a pair of orthogonal coupled modes or a pair of normal ones. The description that is split by the gyromagnetic material is usually referred to as the normal modes of the waveguide and the other is referred to as the coupled modes. In a longitudinally magnetized gyromagnetic waveguide the normal modes are circularly polarized ones and the coupled modes are linear orthogonal ones. Propagation in this type of waveguide is identified with the classic Faraday rotation effect. The nature of the split normal modes of the quadrupole field gyromagnetic rhombic waveguide with the port nomenclature illustrated in Fig. 1

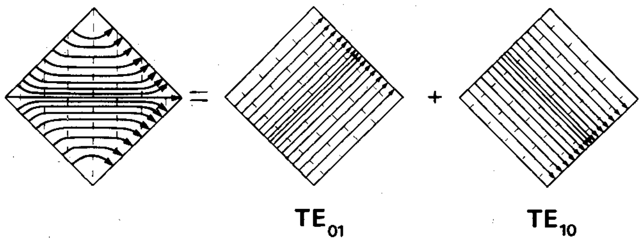


Fig. 2. Normal modes of rhombic waveguide.

may be understood by resolving an incident wave at port 1 into orthogonal TE_{01} and TE_{10} square waveguide modes. This situation is depicted in Fig. 2. Scrutiny of this diagram indicates that the split normal modes of this arrangement correspond to the two possible states of a square gyromagnetic waveguide magnetized perpendicular to the alternating magnetic field in the positive y direction on one side of its symmetry plane and magnetized in the negative y direction on the other side. The two solutions, illustrated in Fig. 3(a), are recognized as the standard two states met in the description of the classic differential phase shift section. It is of note that the permeabilities displayed by the two halves of the waveguide are the same for each of the two possible phenomenological waveguides. This may be appreciated by recalling that the alternating magnetic fields perpendicular to the direct fields are elliptically polarized with opposite hands on either side of the symmetry plane of the waveguides. If the direction of propagation or the polarization of the direct fields is reversed, then the two phase states displayed by the normal modes are interchanged. This is illustrated in Fig. 3(b). The device is therefore nonreciprocal. The related circular quadrupole gyromagnetic waveguide supporting orthogonal TE_{11} modes is illustrated in Fig. 4 and the corresponding normal modes are indicated in Fig. 5(a) and (b).

III. Coupled Mode Theory of Quadrupole Gyromagnetic Waveguide

A knowledge of the normal modes of the quadrupole gyromagnetic waveguide readily permits a coupled mode description. The derivation starts by forming a linear combination of the two normal modes of the waveguide at its coupled ports. The field distributions of the normal modes at the coupled ports are in-phase and out-of-phase in space quadrature TE_{01} modes with propagation constants β_- and β_+. This is illustrated in Fig. 6.

This gives

$$E_x(z) = \frac{1}{2}\exp(-j\beta_- z) + \frac{1}{2}\exp(-j\beta_+ z) \qquad (1a)$$

$$E_y(z) = \frac{1}{2}\exp(-j\beta_- z) - \frac{1}{2}\exp(-j\beta_+ z). \qquad (1b)$$

The preceding equations satisfy the boundary conditions $E_x(0) = 1$ at port 1 and $E_y(0) = 0$ at port 2. These may be simplified by taking out a common factor

$$\exp - j\left(\frac{\beta_- + \beta_+}{2}\right)z. \qquad (2)$$

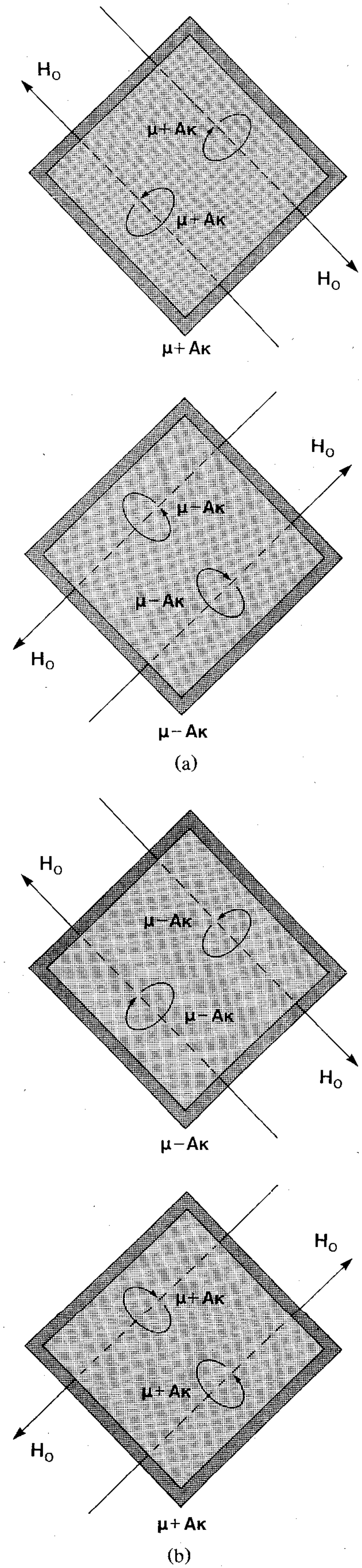


Fig. 3. (a) Normal modes of quadrupole rhombic waveguide for positive direction of propagation. (b) Normal modes of quadrupole rhombic waveguide for negative direction of propagation.

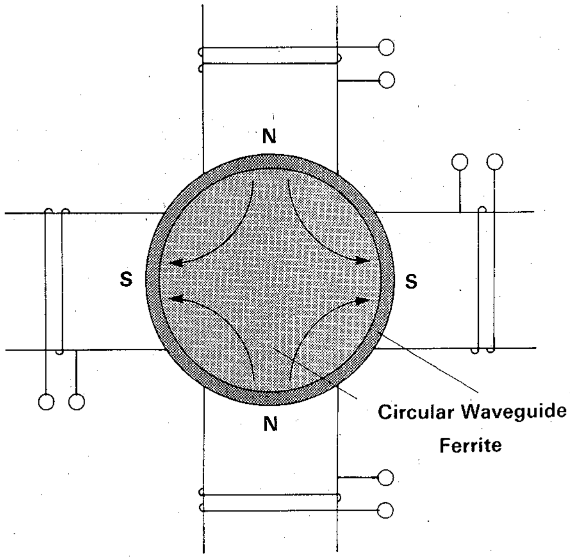


Fig. 4. Schematic diagram of quadrupole circular gyromagnetic waveguide.

The required result is

$$E_x(z) = \cos\left(\frac{\beta_- - \beta_+}{2}\right) z \cdot \exp - j\left(\frac{\beta_- + \beta_+}{2}\right) z \tag{3a}$$

$$E_y(z) = -j \sin\left(\frac{\beta_- - \beta_+}{2}\right) z \cdot \exp - j\left(\frac{\beta_- + \beta_+}{2}\right) z. \tag{3b}$$

This result indicates that there exists a periodic exchange of power between the two polarizations. If

$$\left(\frac{\beta_- - \beta_+}{2}\right) z = \frac{\pi}{4} \tag{4}$$

then the two components combine into a circularly polarized wave of one hand. (The coupled waves corresponding to the boundary conditions $E_x(0) = 0$ at port 1 and $E_y(0) = 1$ at port 2 may be deduced without ado.) If the direction of propagation or the direct magnetic field is altered, then the same input gives rise to the other hand of circular polarization. This feature may be understood by recognizing that the signs of β_+ and β_- are reversed for propagation in the $-z$ direction and furthermore that the phase constants of $\beta_\pm$ are separately interchanged. The required relationships for incident waves at ports 3 and 4 are derived without ado. The notation used here is consistent with the fact that $\beta_- > \beta_+$ below so-called ferrimagnetic resonance.

One possible way to independently couple to each normal mode one at a time is to employ a coupling iris consisting of an inclined slot at $\pm 45°$ to the input port of the quadrupole gyromagnetic waveguide.

IV. Phenomenological Model of Quadrupole Rhombic Gyromagnetic Waveguide

An upper bound on the phase constants of the two normal modes of the rhombic waveguide may be obtained by evaluating the phase constants associated with a square gyromagnetic waveguide with its two halves oppositely magnetized in the transverse plane [16], [19]. An exact solution for the dominant TE mode may be found from a number of different approaches, including direct solution of the fields through

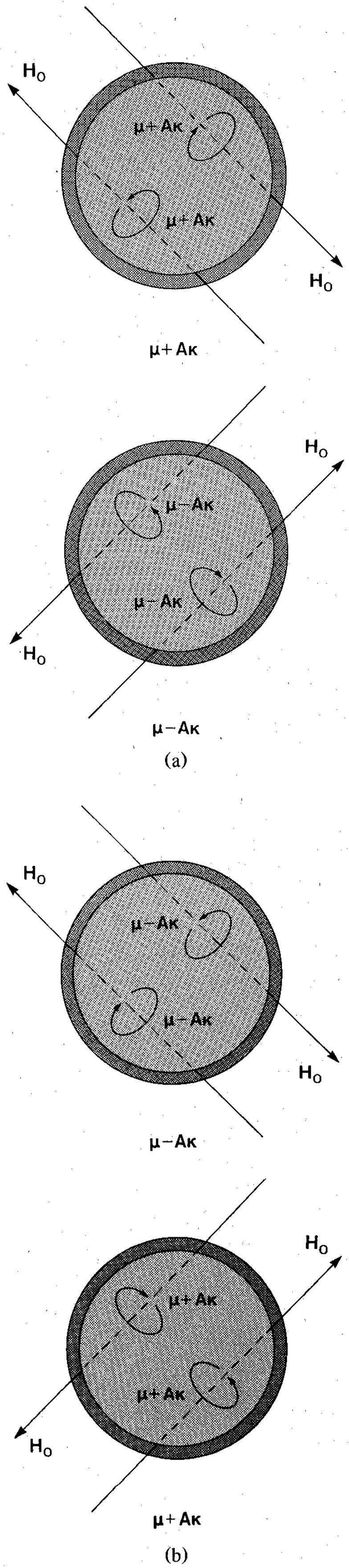


Fig. 5. (a) Normal modes of quadrupole circular waveguide for positive direction of propagation. (b) Normal modes of quadrupole circular waveguide for negative direction of propagation.

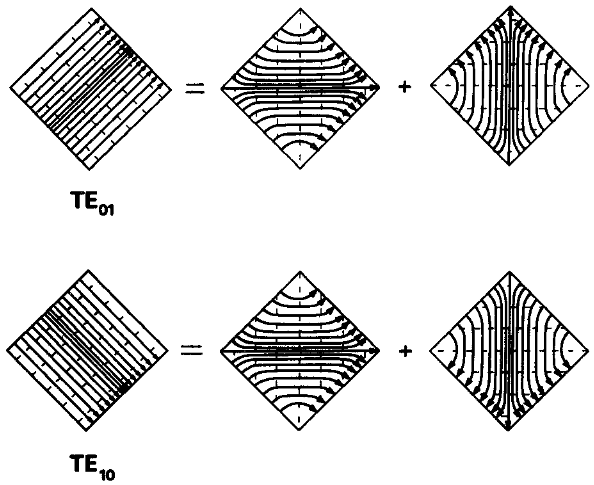


Fig. 6. Normal modes of rhombic waveguide.

Maxwell's equations or by having recourse to the *ABCD* description of the problem. Since the two ferrite regions of such a geometry are magnetized in opposite directions with equal magnitudes, both display the same permeability to a propagating wave; hence the fields are symmetrical. This allows a magnetic wall boundary to be placed at the symmetry plane of the waveguide, so that only a single transversely magnetized section need be solved for.

The *ABCD* matrix description of a magnetized ferrite region loaded between parallel plates and supporting TE-type propagation is a classic result in the literature [45]. For the direct magnetic field applied in the positive y direction, the *ABCD* parameters of such a region of width L are

$$A = \cosh(\gamma_x L) + j\left(\frac{\kappa}{\mu}\right)\left(\frac{\gamma_z}{\gamma_x}\right)\sinh(\gamma_x L) \tag{5a}$$

$$B = j\left(\frac{\omega\mu_0\mu_e}{\gamma_x}\right)\sinh(\gamma_x L) \tag{5b}$$

$$C = -j\left(\frac{\gamma_x}{\omega\mu_0\mu_e}\right)\left[1+\left(\frac{\kappa}{\mu}\right)^2\left(\frac{\gamma_z}{\gamma_x}\right)^2\right]\sinh(\gamma_x L) \tag{5c}$$

$$D = \cosh(\gamma_x L) - j\left(\frac{\kappa}{\mu}\right)\left(\frac{\gamma_z}{\gamma_x}\right)\sinh(\gamma_x L) \tag{5c}$$

where

$$\gamma_x^2 + \gamma_z^2 + \omega^2\mu_0\mu_e\epsilon_0\epsilon_f = 0 \tag{6}$$

and

$$\mu_e = \frac{\mu^2 - \kappa^2}{\mu}. \tag{7}$$

The quantities γ_x and γ_z are separation constants. For the single magnetized region the boundary conditions are

$$E_{y1} = 0 \quad \text{at } x = 0 \tag{8}$$

$$H_{z2} = 0 \quad \text{at } x = \frac{a}{2}. \tag{9}$$

The *ABCD* description of the problem is then

$$\begin{bmatrix} 0 \\ H_{z1} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} E_{y2} \\ 0 \end{bmatrix}. \tag{10}$$

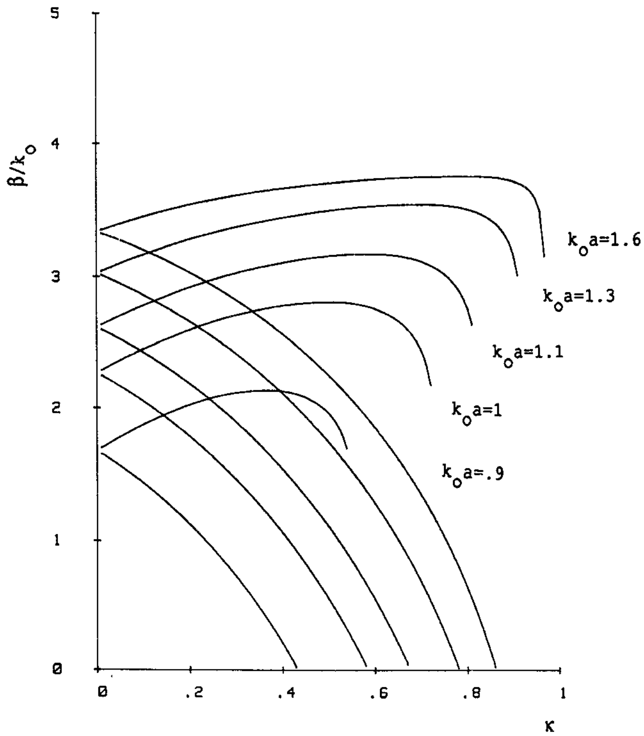


Fig. 7. Normalized split phase constants of rhombic quadrupole gyromagnetic waveguide for parametric values of k_0a ($\epsilon_f = 15$).

This implies that

$$A = \cosh\left(\gamma_x\frac{a}{2}\right) + j\left(\frac{\kappa}{\mu}\right)\left(\frac{\gamma_z}{\gamma_x}\right)\sinh\left(\gamma_x\frac{a}{2}\right) = 0 \tag{11}$$

The last equation is the characteristic equation for a square gyromagnetic waveguide with both halves oppositely magnetized. It may be solved for the phase constants of the normal modes of the waveguide by assuming that the dominant TE_{10} mode is propagating. Fig. 7 indicates the relationship between the split phase constants of this type of waveguide and the off-diagonal element of the tensor permeability for k_0a in the range 0.9 to 1.6. Fig. 8 displays the upper branch of the split phase constants in greater detail for one value of k_0a. This result separately indicates that the cutoff numbers of this type of waveguide are degenerate.

V. Approximate Model of Quadrupole Gyromagnetic Waveguide

A number of models for the differential phase shift of the normal modes of the quadrupole gyromagnetic waveguide are possible. One possibility is that obtained by forming the dispersion relationship of an equivalent anisotropic waveguide with a diagonal permeability

$$[\mu] = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \tag{12}$$

and

$$\mu_x = \mu_z = \mu \pm A\kappa \tag{13}$$

$$\mu_y = 1. \tag{14}$$

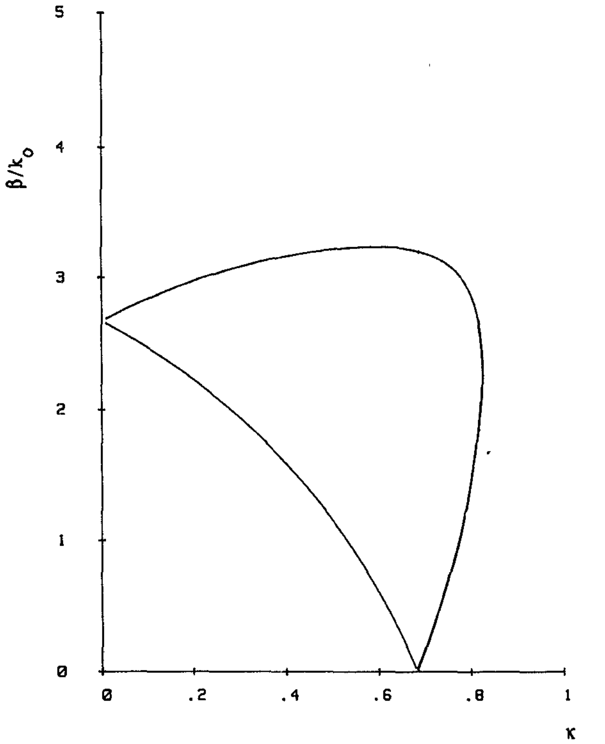


Fig. 8. Normalized split phase constants of rhombic quadrupole gyromagnetic waveguide, showing detail of upper phase curve ($k_0 a = 1.1$, $\epsilon_f = 15$).

Another possibility is to replace

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \tag{15}$$

in a perturbation formulation of the two possible phase constants. The solution to the first approximation is

$$\beta_{\pm}^2 = k_0^2 \epsilon_f (\mu \pm A\kappa) - \left(\frac{\pi}{a}\right)^2 \tag{16}$$

and that of the second is

$$\beta_{\pm} = \beta_0 + \frac{k_0^2 \epsilon_f}{2\beta_0}(1 - \mu \pm A\kappa) \tag{17}$$

where for a square waveguide β_0 is given by

$$\beta_0^2 = k_0^2 \epsilon_f - \left(\frac{\pi}{a}\right)^2. \tag{18}$$

A is a constant between 0 and 1 to cater for the fact that the alternating magnetic field is elliptically rather than circularly polarized in the plane perpendicular to the direct magnetic field and also that each half of the waveguide is not uniformly magnetized. The anisotropic and perturbation solutions, unlike the closed-form one, display split cutoff numbers as well as split phase constants. This discrepancy may be understood by recognizing that the approximate formulations assume that the fields are not perturbed by the gyromagnetic effect.

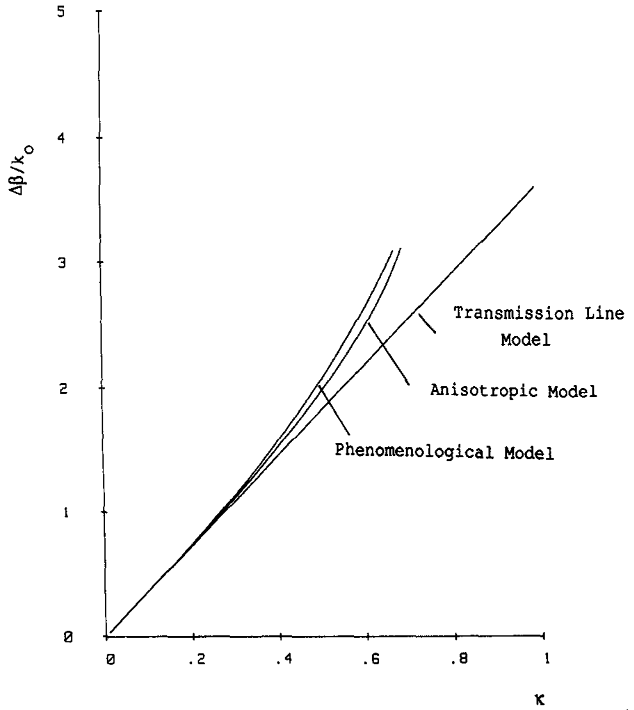


Fig. 9. Differential phase shift of rhombic quadrupole gyromagnetic waveguide using phenomenological, anisotropic, and transmission line models ($k_0 a = 1.1$, $\epsilon_f = 15$).

Rearranging either relationship assuming symmetrical splitting of the phase constants, with $\mu = 1$, readily gives

$$\frac{\beta_+ - \beta_-}{k_0} \approx A\left(\frac{k_0 \epsilon_f}{\beta_0}\right)\kappa. \tag{19}$$

The constant A may be deduced from measurement, by comparison with the phenomenological model, or by comparisons with the relationship given by Boyd in [23]:

$$\frac{\beta_+ - \beta_-}{k_0} \approx A'\left(\frac{k_c}{k_0}\right)\frac{\kappa}{\mu}. \tag{20}$$

For a square waveguide

$$k_c = \pi / a \quad \text{and} \quad A' \approx 4/\pi. \tag{21}$$

Fig. 9 separately indicates the agreement between the phenomenological, the anisotropic, and the Boyd formulation of the problem for one typical value of $k_0 a$. Scrutiny of this result indicates that it is adequate for modest values of κ.

Making use of these two relationships gives

$$A = \frac{4 k_c \beta_0}{\pi \epsilon_f k_0^2} \tag{22}$$

so that

$$\mu \pm A\kappa \approx \mu \pm \left(\frac{4 k_c \beta_0}{\pi \epsilon_f k_0^2}\right)\kappa. \tag{23}$$

The relationship between the split phase constants of the phenomenological, anisotropic, and perturbation models is depicted in Fig. 10.

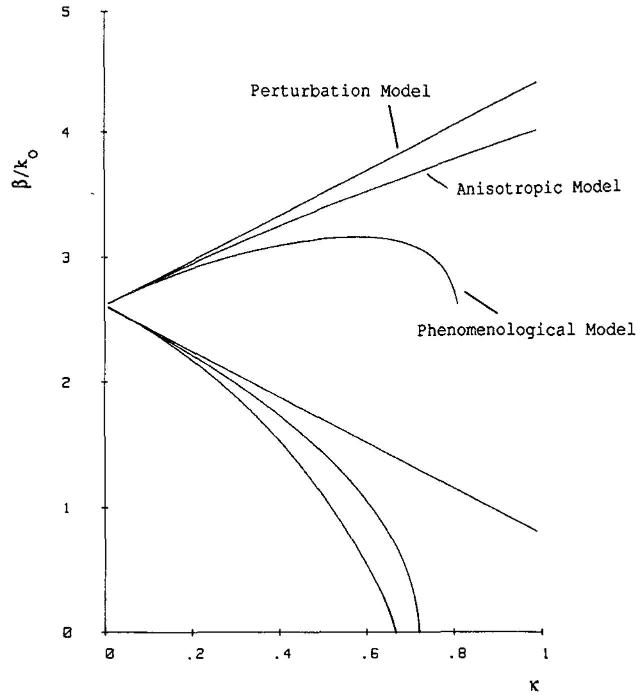


Fig. 10. Normalized split phase constants of rhombic quadrupole gyromagnetic waveguide using phenomenological, anisotropic, and perturbation models ($k_0a = 1.1$, $\epsilon_f = 15$).

VI. Edge Mode Effect

A common feature of a transversely magnetized parallel-plate gyromagnetic waveguide is a nonreciprocal edge mode or field displacement effect [34]–[41], [44]. Such an effect is also present in the quadrupole waveguide investigated in this work.

The power, electric, and magnetic fields of the two normal modes are indicated in Figs. 11 and 12. The existence of planes of circular polarization with different hands on either sides of the symmetry plane is of note in the illustrations.

In obtaining these results the amplitude constant in the description of H_z has been adjusted so that

$$P_t' = k_0^2 P_t = 1 \tag{24}$$

where

$$P_t = \frac{1}{2}\int_0^a \int_0^a \mathrm{Re}(\boldsymbol{E}\times\boldsymbol{H}^*)\, ds. \tag{25}$$

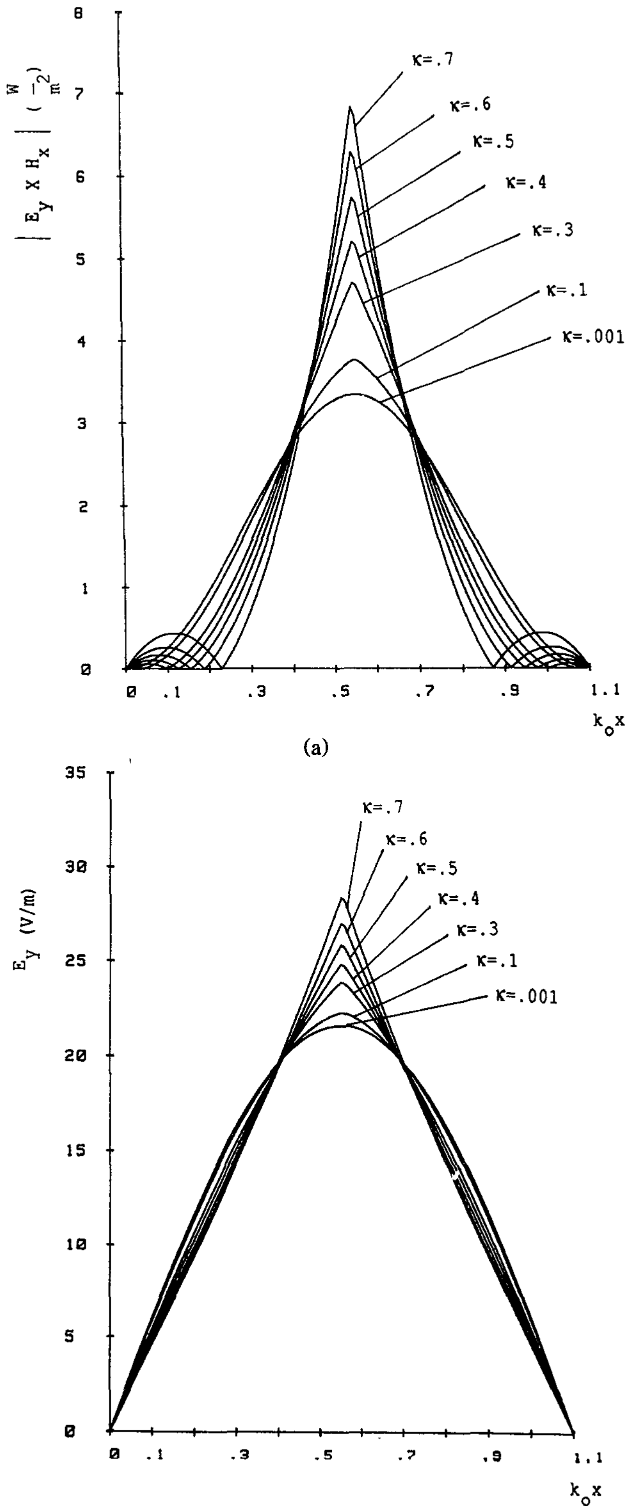
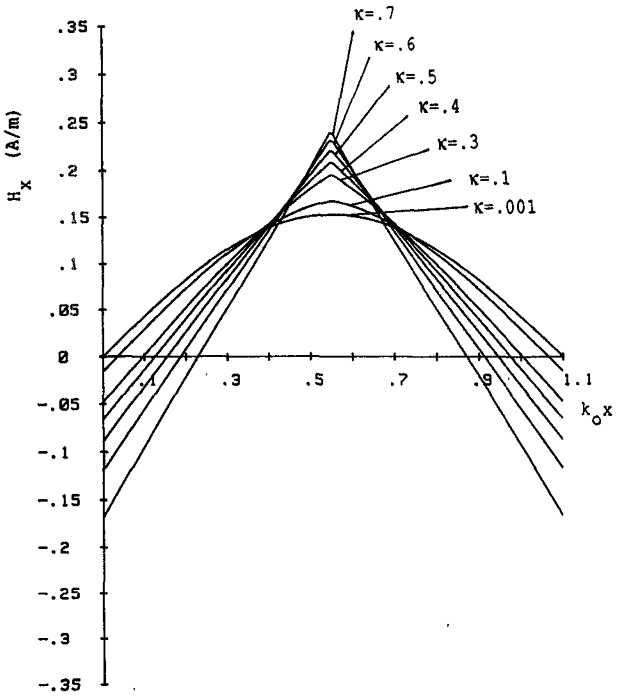


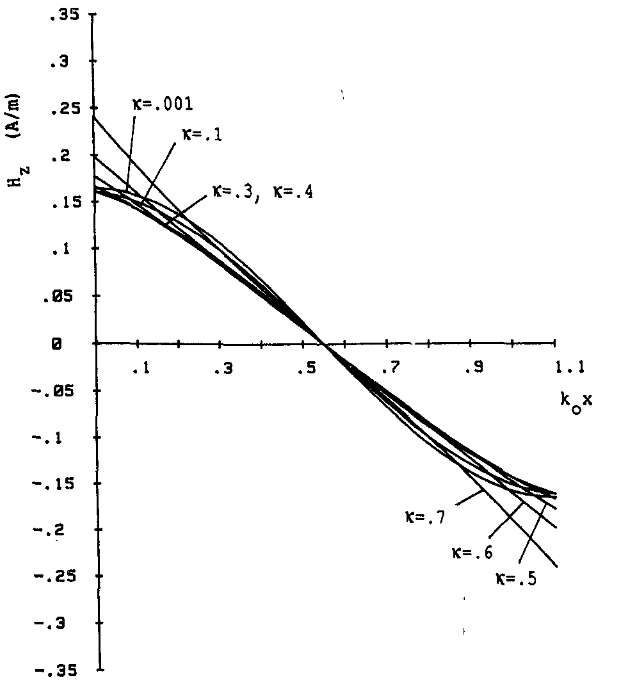
Fig. 11. (a) Normalized power distribution in rhombic quadrupole gyromagnetic waveguide for positive direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$). (b) Electric field distribution in rhombic quadrupole gyromagnetic waveguide for positive direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$). *(Continued on next page)*

VII. Quadrupole Half-Wave Plate

An important application of the quadrupole gyromagnetic waveguide is in the design of an electronic half-wave plate employing a rotating quadrupole magnetic field [13], [18], [19], [25], [27], [31], [33]. One practical geometry is indicated in Fig. 13. An important property of this plate is that the polarization of a linearly polarized wave is rotated by twice the angle that the quadrupole magnetic field makes in the transverse plane; another is that a circularly polarized wave with one hand of polarization at one pair of ports is converted to one with the opposite hand at the other pair of ports but phase shifted by an angle 2θ. This situation is analogous to that met in connection with the description of a reciprocal half-wave plate orientated at $\pm 45°$ to the ports of the round waveguide. If this plate is placed between recipro-



(c)

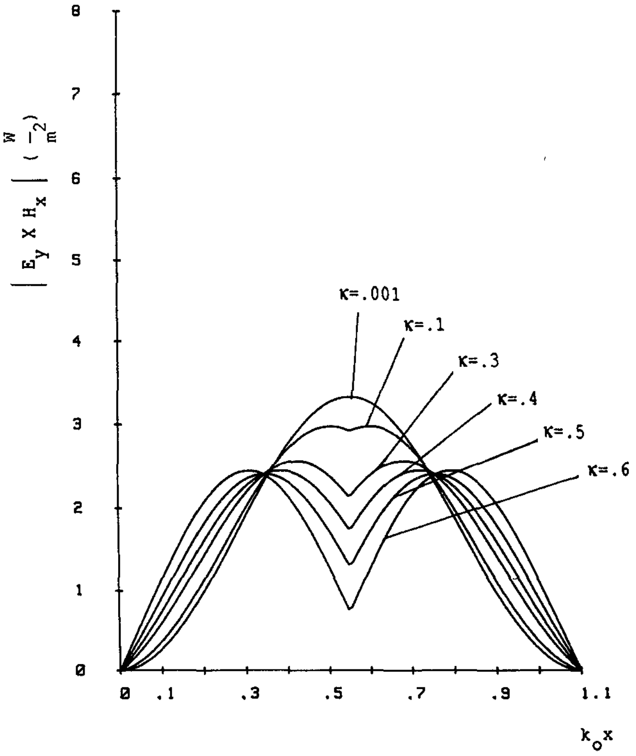


(d)

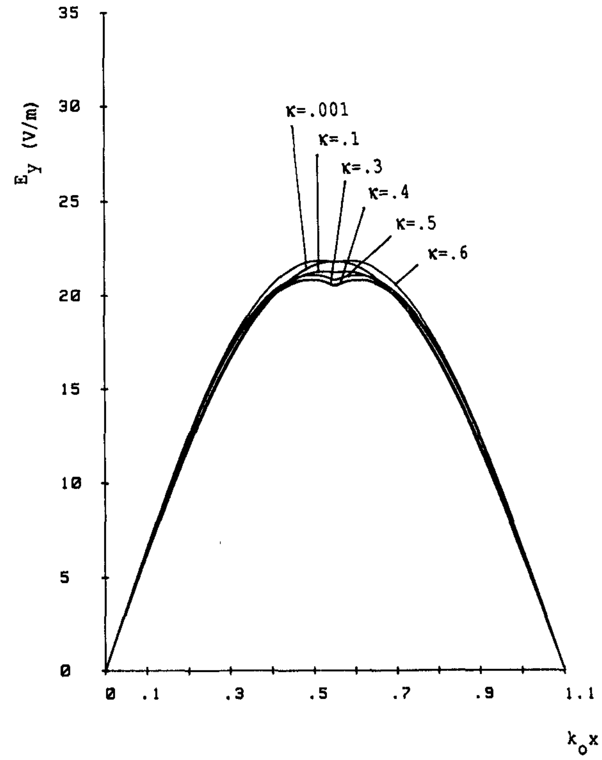
Fig. 11. (*Continued*) (c) X-directed magnetic field distribution in rhombic quadrupole gyromagnetic waveguide for positive direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$). (d) Z-directed magnetic field distribution in rhombic quadrupole gyromagnetic waveguide for positive direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$).

cal quarter-wave plates, then it provides a continuously increasing phase shift which is linear in time to the same extent that the angular magnetic field is constant. The ensuing structure, however, is now nonreciprocal.

The operation of the half-wave plate may be understood by decomposing an input signal at port 1 (say) in Fig. 13 into

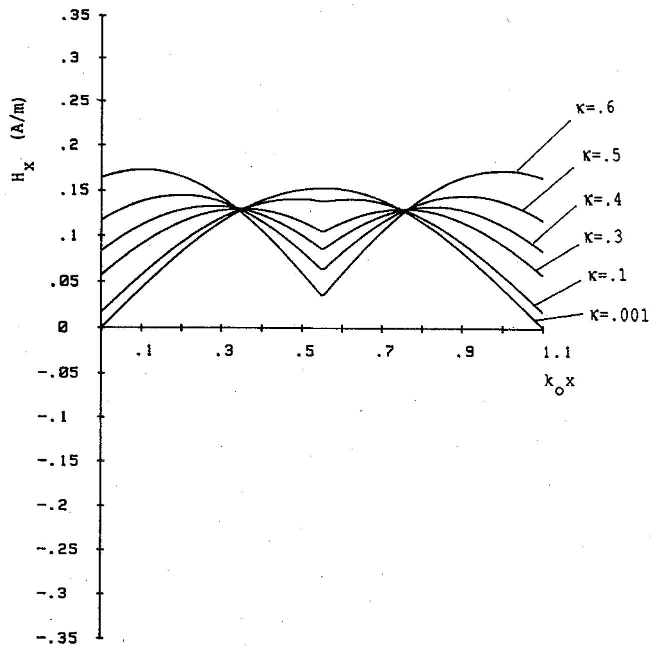


(a)



(b)

Fig. 12. (a) Normalized power distribution in rhombic quadrupole gyromagnetic waveguide for negative direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$). (b) Electric field distribution in rhombic quadrupole gyromagnetic waveguide for negative direction of propagation ($k_0a = 1.1$, $\epsilon_f = 15$). (*Continued on next page*)



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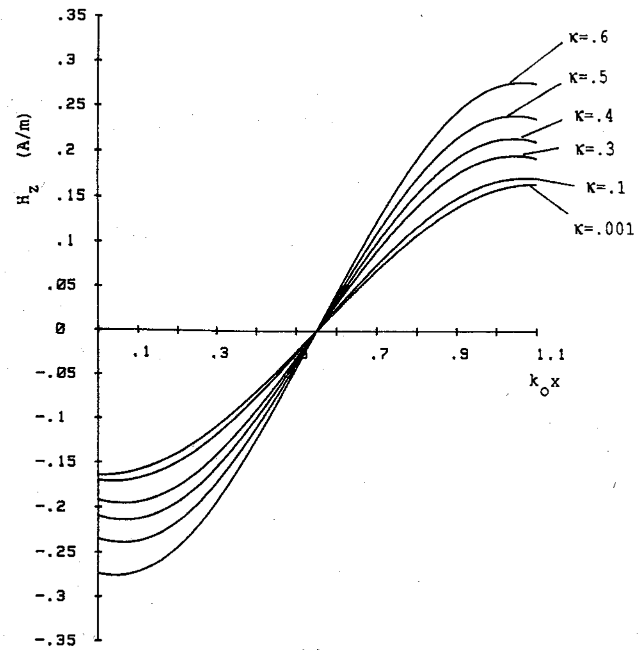

(d)

Fig. 12. (*Continued*) (c) X-directed magnetic field distribution in rhombic quadrupole gyromagnetic waveguide for negative direction of propagation ($k_0 a = 1.1$, $\epsilon_f = 15$). (d) Z-directed magnetic field distribution in rhombic quadrupole gyromagnetic waveguide for negative direction of propagation ($k_0 a = 1.1$, $\epsilon_f = 15$).

the two normal modes of the gyromagnetic waveguide in the manner indicated in Fig. 14. This gives

$$E_x(z) = \cos^2\theta \exp(-j\beta_- z) + \sin^2\theta \exp(-j\beta_+ z) \quad (26a)$$

and

$$E_y(z) = \sin\theta\cos\theta \exp(-j\beta_- z) - \sin\theta\cos\theta \exp(-j\beta_+ z). \quad (26b)$$

If the preceding two relationships are written as

$$E_x(z) = A\exp(-j\beta_- z) + B\exp(-j\beta_+ z) \quad (27a)$$

$$E_y(z) = C\exp(-j\beta_- z) + D\exp(-j\beta_+ z) \quad (27b)$$

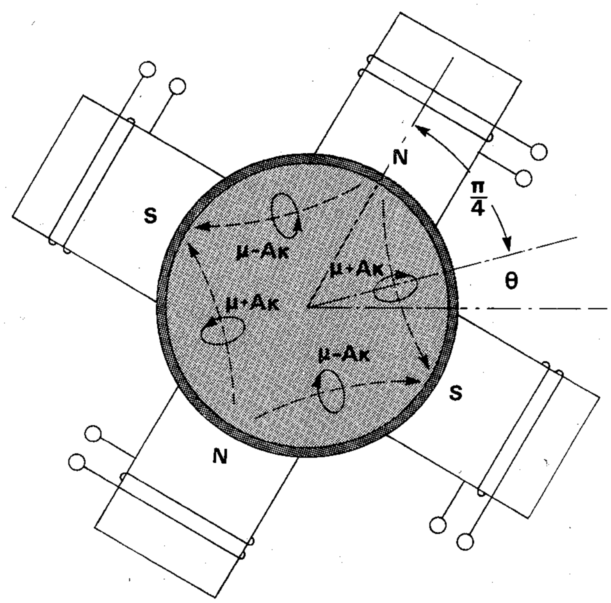

Fig. 13. Coil arrangement for electronic rotable half-wave plate.

where

$$A = \frac{1}{2}(1+\cos 2\theta) \quad (28a)$$

$$B = \frac{1}{2}(1-\cos 2\theta) \quad (28b)$$

$$C = \frac{1}{2}\sin 2\theta \quad (28c)$$

$$D = -\frac{1}{2}\sin 2\theta \quad (28d)$$

then these are recognized as the classic pair of coupled wave equations met in the description of waveguides with unequal propagation constants. This result indicates that if the angle θ is different from $\pi/4$ then the normal modes have unequal amplitudes in the two coupled waveguides.

The preceding equations satisfy the boundary conditions $E_x(0) = 1$ at port 1 and $E_y(0) = 0$ at port 2.

Taking out a common factor

$$\exp - j\left(\frac{\beta_- + \beta_+}{2}\right)z$$

readily gives

$$E_x(z) = \left[\cos\left(\frac{\beta_- - \beta_+}{2}\right)z + j\cos(2\theta) \cdot \sin\left(\frac{\beta_- - \beta_+}{2}\right)z\right]\exp - j\left(\frac{\beta_- + \beta_+}{2}\right)z \quad (29a)$$

$$E_y(z) = j\left[\sin(2\theta)\sin\left(\frac{\beta_- - \beta_+}{2}\right)z\right]\exp - j\left(\frac{\beta_- + \beta_+}{2}\right)z. \quad (29b)$$

If $\theta = \pi/4$ then these relationships reduce without ado to

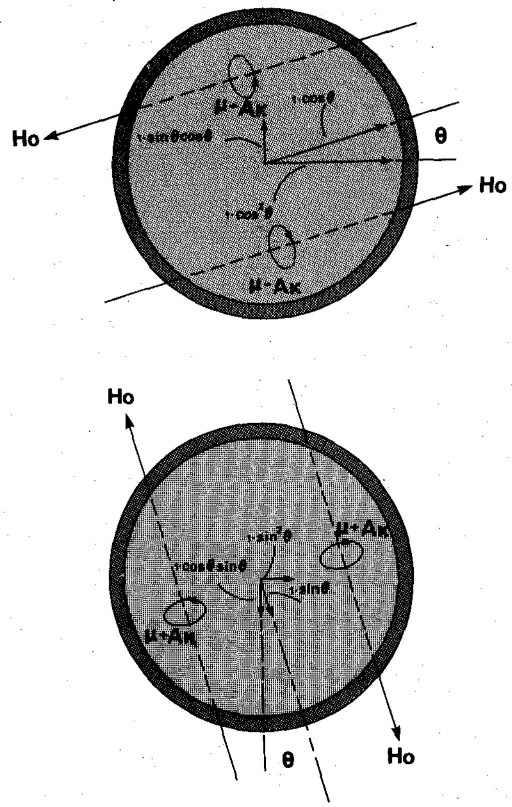

Fig. 14. Normal modes of electronic rotable half-wave plate.

those given by (3a) and (3b). If

$$\left(\frac{\beta_- - \beta_+}{2}\right) z = \frac{\pi}{2}$$

then

$$E_x(z) = j\cos(2\theta)\cdot\exp - j\left(\frac{\beta_- + \beta_+}{2}\right) z \qquad (30a)$$

$$E_y(z) = j\sin(2\theta)\cdot\exp - j\left(\frac{\beta_- + \beta_+}{2}\right) z \qquad (30b)$$

and a horizontally polarized input wave is rotated by an angle 2θ, as asserted.

The general description of this network for an input at any port,

$$S = \begin{bmatrix} 0 & 0 & -\cos 2\theta & -\sin 2\theta \\ 0 & 0 & -\sin 2\theta & \cos 2\theta \\ \cos 2\theta & \sin 2\theta & 0 & 0 \\ \sin 2\theta & -\cos 2\theta & 0 & 0 \end{bmatrix} \qquad (31)$$

is derived by taking each of the other ports one at a time as an input port. This matrix has the form met in the description of the dielectric half-wave plate except that it is nonreciprocal.

VIII. Conclusions

A practical waveguide of some interest in the design of ferrite control devices is a rhombic or circular gyromagnetic one magnetized by a direct quadrupole magnetic field. A perturbation, an anisotropic, and an approximate closed-form description of the problem have been derived based on an understanding of the two normal modes of this waveguide. All three solutions are compatible at the origin with that of the transmission model of the same problem. A study of the fields in this type of waveguide reveals a classic edge mode effect.

Appendix

The split phase constants of the quadrupole phase shifter may also be compared to that met in the description of the Faraday rotation problem:

$$\beta_\pm^2 = \left[k_0^2\epsilon_f - \left(\frac{1.84}{R}\right)^2\right](\mu \pm A\kappa) \qquad (A1)$$

where

$$A = 0.84$$

for a circular waveguide.

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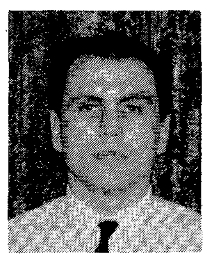

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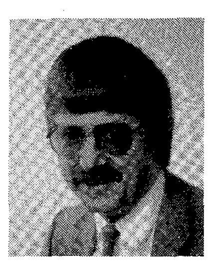

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