In conclusion, a variational expression is presented for the line capacitance of the CPW on a single-crystal sapphire substrate with its optical axis inclined. Numerical results by the Ritz procedure are also presented.

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Nonreciprocal Propagation Characteristics of YIG Thin Film

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***Abstract*—The characteristics of an optical nonreciprocal phase shifter, with which optical circulators can be constructed, are investigated. We have measured the nonreciprocal phase shift of an appropriately magnetized yttrium iron garnet (YIG) thin film and thus confirmed experimentally that an AIR/YIG/GGG structure can function as an optical nonreciprocal phase shifter.**

I. Introduction

Nonreciprocal devices, such as isolators and circulators, are necessary in optical communication systems in order to avoid self-oscillation due to reflections in the laser amplifier. At present, we can get optical isolators of practically good performance only in a bulk form. However, they are not realized in a thin-film waveguide form which is compatible with integrated optical circuits in the future systems. Several workers have investigated thin-film optical isolators using unidirectional TE–TM mode conversion in magnetooptic materials [1]–[4], but their results are considerably unsatisfactory. The difficulties arise from the following reasons. 1) It is necessary to use anisotropic materials, such as $LiNbO_3$ or $LiIO_3$, in a proper way. But, these materials cannot be grown on magnetic materials because of their lattice mismatch. Besides, the gap between the anisotropic material and the thin film is a critical factor and it is almost impossible to get a uniform optical contact over a long distance. 2) It is required to control the thickness of thin films very accurately. Typically, the accuracy of 0.1 percent to 1.0 percent of the optical wavelength is required. These two requirements are necessary to make the TE and TM modes phase match, which is inevitable if unidirectional TE–TM mode conversion in a magnetooptic material is used.

By the way, a different type of the optical circulator, which makes use of nonreciprocal phase shift in magnetooptic materials for TM modes, has been proposed [5]. The advantages of this structure are: 1) no need of phase matching, therefore no need of anisotropic materials and higher tolerances of the film thickness; and 2) ease of excitation of eigenmodes as they are pure TM modes.

We observed that the TM_0 mode suffers a nonreciprocal phase shift in a properly magnetized YIG thin film. In Section II, we treat theoretically the optical nonreciprocal phase shifter, which is the important part of the optical circulator. Next we also show the results of measurement of nonreciprocal phase shift in Section III.

II. Optical Nonreciprocal Phase Shifter (ONPS)

The schematic diagram of the optical circulator using ONPS is shown in Fig. 1. This circuit functions as follows. A wave entering waveguide 1 from the left is split into two waves of equal amplitudes by means of the 3-dB coupler I. The two waves then propagate in the two waveguides, one of which is ONPS, and are again combined by means of the 3-dB coupler II. With proper selection of parameters we can design this structure in such a way that behind the second 3-dB coupler all the energy is guided in only one waveguide (e.g., in waveguide 4). If ONPS is designed in such a manner that forward and reverse traveling waves have phase shifts different by π, then for the reverse traveling wave from waveguide 4 all the energy will be coupled into waveguide 2, not into waveguide 1. Similarly, a wave entering waveguide 2 from the left comes out in waveguide 3, and the reverse traveling wave from waveguide 3 goes to waveguide 1.

ONPS consists of an asymmetric three-layer waveguide structure (Fig. 2). Each medium is assumed to be a lossless magnetooptic material with dielectric tensor

$$\tilde{\epsilon}_i = \epsilon_0 \begin{pmatrix} \epsilon_i & 0 & 0 \\ 0 & \epsilon_i & j\alpha_i \\ 0 & -j\alpha_i & \epsilon_i \end{pmatrix} \qquad (i=1,2,3).$$

It is said that there exists magnetic birefringence in the bulk case of YIG [6]. Here, we neglect it because it is considered relatively small compared to the magnetooptic anisotropy. The dc magnetizing field is applied in the X-axis direction. And the wave propagates in the Z-axis direction. We solve the exact eigenvalue equation for this structure [7] and obtain the characteristic equation for the TM modes

$$\tan(kd) = \frac{\dfrac{k}{\epsilon_2'}\left\{\dfrac{p}{\epsilon_1'} + \dfrac{q}{\epsilon_3'} + \left(\dfrac{\alpha_1}{\epsilon_1\epsilon_1'} - \dfrac{\alpha_3}{\epsilon_3\epsilon_3'}\right)\beta\right\}}{C_0 + C_1\beta + C_2\beta^2} \tag{1}$$

where

$$C_0 = \left(\frac{k}{\epsilon_2'}\right)^2 - \frac{p}{\epsilon_1'}\frac{q}{\epsilon_3'}$$

$$C_1 = \frac{p}{\epsilon_1'}\left(\frac{\alpha_3}{\epsilon_3\epsilon_3'} - \frac{\alpha_2}{\epsilon_2\epsilon_2'}\right) + \frac{q}{\epsilon_3'}\left(\frac{\alpha_2}{\epsilon_2\epsilon_2'} - \frac{\alpha_1}{\epsilon_1\epsilon_1'}\right)$$

$$C_2 = \left(\frac{\alpha_2}{\epsilon_2\epsilon_2'} - \frac{\alpha_1}{\epsilon_1\epsilon_1'}\right)\left(\frac{\alpha_2}{\epsilon_2\epsilon_2'} - \frac{\alpha_3}{\epsilon_3\epsilon_3'}\right)$$

$$\epsilon_i' = (\epsilon_i^2 - \alpha_i^2)/\epsilon_i$$

$$\beta^2 = \epsilon_1' k_0^2 + p^2 = \epsilon_2' k_0^2 - k^2 = \epsilon_3' k_0^2 + q^2 \qquad (k_0^2 = \omega^2\epsilon_0\mu_0).$$

β represents the propagation constant in the Z-axis direction. Because of nonzero linear terms in β, this equation shows that

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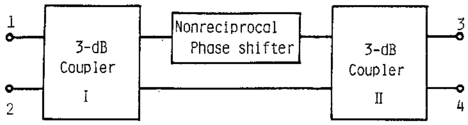

Fig. 1. Schematic diagram of the optical circulator using the nonreciprocal phase shifter.

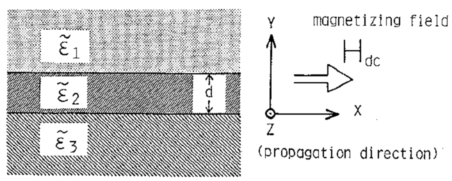

Fig. 2. Assumed magnetooptic waveguide for the nonreciprocal phase shifter.

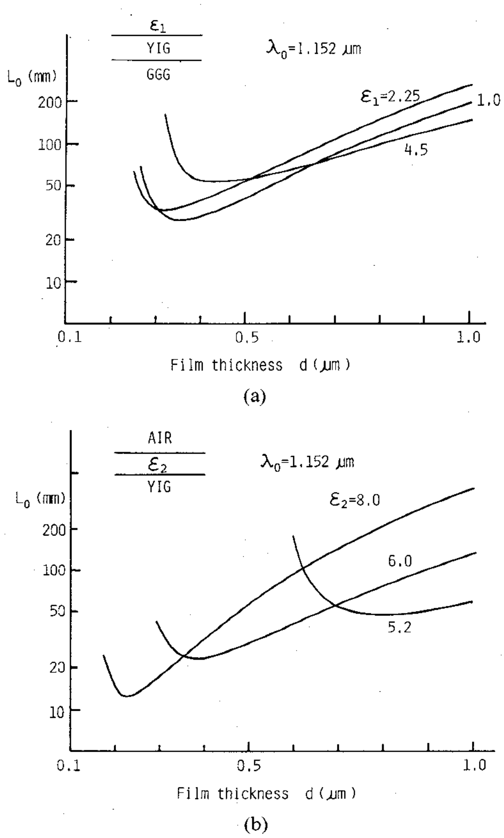

Fig. 3. Required length L_0 for π phase difference between forward and reverse traveling TM_0 waves as a function of film thickness d. The magnetooptic material (YIG) is used as (a) the guiding thin film, and (b) the substrate. (The material parameters are taken from [2] for YIG and [3] for GGG).

there are nonreciprocal solutions; that is, β depends on the direction of propagation.

Now, consider the two practical cases.

1) Only the waveguiding film, that is, region-2, is composed of a magnetooptic material ($\alpha_1 = \alpha_3 = 0$).

Fig. 3(a) shows the propagation length L_0, which is required for π phase difference between forward and reverse traveling TM_0 waves at the wavelength of 1.152 μm. L_0 is defined by the following equation:

$$L_0 = \pi / |\beta_+ - \beta_-| \tag{2}$$

where $\beta_\pm$ denotes the propagation constants in the positive and negative Z-axis direction. The assumed magnetooptic material is YIG, which has a loss less than 0.1 dB/cm in the range between

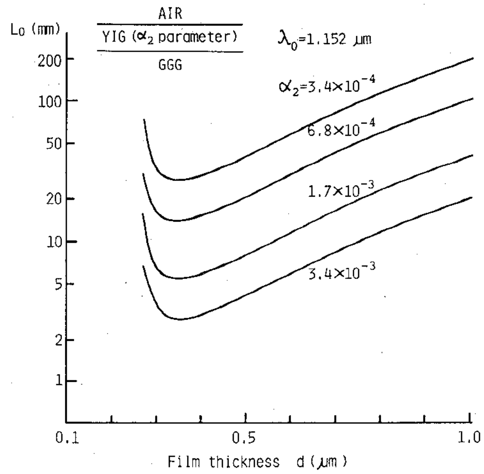

Fig. 4. The change of the required length L_0 as a parameter of α_2. α_2 represents the magnitude of off-diagonal elements of YIG dielectric tensor.

1.2 and 5.0 μm [8] and the following dielectric tensor [2]:

$$\begin{pmatrix} 4.963 & 0 & 0 \\ 0 & 4.963 & j3.4\times10^{-4} \\ 0 & -j3.4\times10^{-4} & 4.963 \end{pmatrix}.$$

The GGG substrate is necessary for epitaxial growth of YIG thin film.

When the dielectric constant of the top layer is 1.0, the required L_0 takes the minimum value, about 27 mm, at the film thickness of 0.35 μm. This length is quite long for an integrated device. But, when the specific rotation of a magnetooptic material is improved, the required length L_0 is reduced as shown in Fig. 4. Namely, L_0 becomes about 1/10 when the value of α, which is the imaginary part of the off-diagonal element of the dielectric tensor and is approximately proportional to the specific rotation, becomes ten times. It is possible to improve the specific rotation of YIG crystal by doping bismuth [9].

The change of L_0 versus the film thickness d in the vicinity of the minimum point is very gradual. That is to say, this structure has fairly wide tolerance of film thickness control. Furthermore, as we mentioned in the preceding section, in this structure no other anisotropic material than the magnetooptic one is necessary. These two points are favorable for the fabrication of thin film waveguide devices.

2) Only the substrate, region-3, is composed of a magnetooptic material ($\alpha_1 = \alpha_2 = 0$).

When we use the same YIG as the substrate, the required L_0 shows dependence on the film thickness d as is shown in Fig. 3(b). The larger the dielectric constant of the film ϵ_2 means the shorter the minimum L_0, while the change of L_0 in the vicinity of the minimum point becomes abrupt as ϵ_2 becomes larger.

For the TE modes, the characteristic equation is

$$\tan(kd) = \frac{(p+q)k}{k^2 - pq} \tag{3}$$

$$\beta^2 = \epsilon_1 k_0^2 + p^2 = \epsilon_2 k_0^2 - k^2 = \epsilon_3 k_0^2 + q^2.$$

There is no linear term in β, and thus, no nonreciprocal solution.

III. Measurement of Nonreciprocal Phase Shift in YIG Thin Film

In this section, we report the measurement of the nonreciprocal phase shift, which we have performed on the YIG ($Y_3Fe_5O_{12}$) single crystal film grown on the {1 1 1} oriented GGG

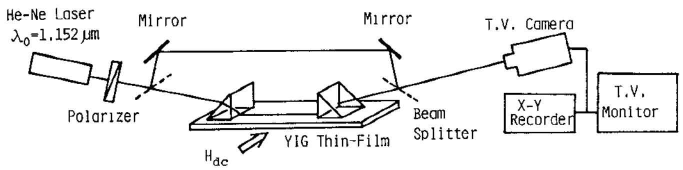

Fig. 5. Setup for the measurement of phase shift.

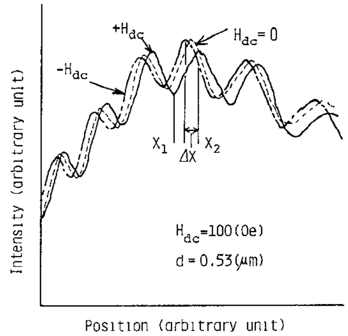

Fig. 6. Example of observed fringe shift. $\Delta\theta = \Delta X \cdot \pi / |X_1 - X_2|$.

($Gd_3Ga_5O_{12}$) substrate by CVD method. We use the notation $\Delta\theta$ to express the quantity of nonreciprocal phase shift, namely, the phase shift difference between forward and reverse traveling waves.

Fig. 5 shows the setup for the measurement of $\Delta\theta$. It consists of a Mach–Zehnder interferometer. The light is coupled into and out from the film by using rutile prisms. By measuring the amount of fringe shift, we can measure the phase shift of the propagating wave in the YIG thin film, which is caused by reversing the direction of dc magnetizing field applied in the plane of YIG thin film and perpendicular to the direction of wave propagation. Reversing the direction of applied magnetizing field is equivalent to reversing that of wave propagation.

Fig. 6 shows an example of observed fringe shift. The abscissa indicates the position on the line transverse to the light path before the TV camera. The broken line indicates the fringe, which is observed when the applied magnetizing field is zero. When the magnetizing field is applied, the fringe shifts as indicated by the solid line. By reversing the direction of the magnetizing field, the fringe shifts in the opposite direction as indicated by the dash-dotted line. Nonreciprocal phase shift $\Delta\theta$ is given by

$$\Delta\theta = \frac{\Delta X}{|X_1 - X_2|} \cdot \pi. \tag{4}$$

Here, $|X_1 - X_2|$ denotes the interval between a bright fringe and a dark one, and ΔX means the amount of fringe shift caused by reversing the direction of applied magnetizing field.

We measured $\Delta\theta$ of TM_0 mode for the propagation lengths of 22 and 37 mm. The results of the measurements are plotted in Fig. 7. The thickness of YIG thin film is 0.53 μm, and the wavelength of the light is 1.152 μm. $\Delta\theta$ is saturated at $|H_{dc}| \geqslant 150$ Oe and is proportional to the propagation length. For the propagation length of 37 mm, the measured $\Delta\theta$ is about 0.6π, while the calculated one is 0.84π as is evident from Fig. 3(a). The off-diagonal element of the dielectric tensor of YIG used in the preceding calculation is $j3.4 \times 10^{-4}$. It should be noticed that we adopted this value just as an example. In fact, it varies depending on the reference (see e.g., [1] and [2]). The YIG thin film used in our measurement may possess a smaller specific rotation, though it could not be measured because of its thinness. The point especially emphasized is that it is confirmed experimentally that this structure can function as the optical nonreciprocal phase shifter for the TM_0 mode.

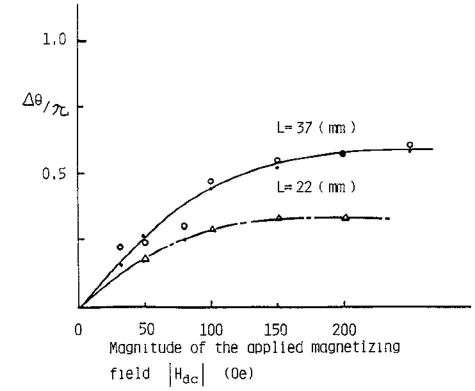

Fig. 7. Measured phase difference between forward and reverse traveling TM_0 waves ($\Delta\theta$) versus the magnitude of the applied dc magnetizing field (H_{dc})

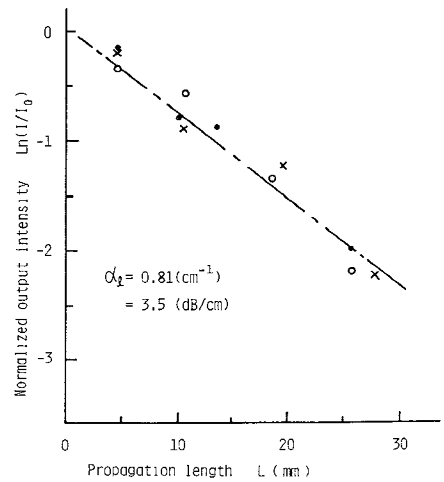

Fig. 8. Intensity of the light coupled out of the film as a function of propagation length L. Measured values are plotted. α_l means the attenuation coefficient.

Besides we confirmed experimentally that the TE_0 mode does not suffer nonreciprocal phase shift. This agrees with the theoretical consideration.

We measured the attenuation coefficient of this YIG thin film by sliding-prism loss measurement method [10]. Fig. 8 shows the measured normalized output intensity as a function of propagation length. The attenuation coefficient is about 3.5 dB/cm at the wavelength of 1.152 μm for the TM_0 mode with no magnetizing field. This attenuation coefficient includes both the intrinsic absorption of YIG crystal and the scattering loss.

IV. Summary

We have measured the nonreciprocal phase shift in YIG thin film and confirmed experimentally that the AIR/YIG/GGG structure can function as an optical nonreciprocal phase shifter for the TM_0 mode but not for the TE_0 mode. However, the required length and the attenuation coefficient of the YIG thin film are too large for a practical integrated optical circuit device. It is possible to reduce the required length for nonreciprocal phase shifter by using two $\pi/2$ nonreciprocal phase shifters in such a manner as in Fig. 9. Furthermore, in order to make a practical device, it is necessary to improve the figure of merit of

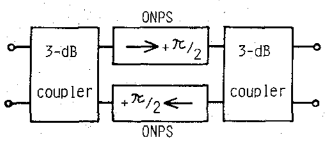

Fig. 9. The required length L_0 for nonreciprocal phase shifter becomes 1/2 by using two $\pi/2$ ONPS's.

the magnetooptic thin film together with fabricating good 3-dB couplers. Further work along these lines is under way.

Acknowledgment

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Patent Abstracts

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4,291,415 Sep. 22, 1981

Microwave Integrated Circuit Double Balanced Mixer

Inventor: **Charles D. Buntschuh.**
Assignee: **Microwave Associates, Inc.**
Filed: **Dec. 3, 1979.**

Abstract—Double-balanced mixers of the star-configuration type for microwave-frequency electromagnetic waves have a balanced four-wire line realized with a pair of wires on each side of a dielectric substrate, means to feed a first-frequency wave to the line in a parallel-mode, and means to feed a second-frequency wave to the line in a transverse-mode. These waves may be RF and LO signals, respectively, or vice versa. A common star-configuration point is provided, and four diodes in a star configuration are connected to it, one from each wire. IF output is between the common star-configuration point and a common reference terminal (e.g.: ground) for the mixer. The mixer can be fed from balanced or unbalanced or unbalanced RF and/or LO input lines.

10 Claims, 16 Drawing Figures