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PHASE MATCHED OPTICAL DIELECTRIC WAVEGUIDE USING 'THE ARTIFICIAL ANISOTROPIC STRUCTURE'

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ABSTRACT

Phase matching technique by 'the artificial anisotropic structure' in the optical dielectric waveguide is proposed. A thin film mode converter can be realized by this technique. Mode conversion is estimated approximately.

Introduction

Optical nonreciprocal devices, such as isolators and circulators are indispensable for laser communication systems. Thin film optical isolators are unidirectional waveguides and will play an important role in integrated optical circuits. Several types of thin film optical isolators have been proposed. Wang et al.[1] have studied the use of gyrotropic and anisotropic materials which give rise to mode conversion between the TE and TM modes in a thin film optical waveguide and mentioned the possibility of using them to realize an isolator or a circulator. This structure is called the tandem type, in which gyrotropic and anisotropic materials are placed in tandem on top of a dielectric waveguide. As a more practical alternative to this structure, the isolators of sandwich structure have been proposed by Warner[2],[3], in which a magneto-optic and an optical anisotropic materials are stratified. In both structures, there exist two serious problems. One is that the tolerance of film thickness deviation is very severe[2],[4], and the other is that the optical anisotropic crystal cannot be grown on the magnetooptic one because of their lattice mismatch[3]. Castéra et al. have proposed another configuration of an optical isolator[5]. They used the Faraday and Cotton-Mouton effects in a rather thick magnetooptic film for a gyrotropic and an anisotropic mode converter, respectively. And the TE_0 and TM_0 modes are degenerated through an induced epitaxial birefringence.

So far we have mentioned only devices which make use of the mode conversion effect. There are some other proposals which do not use it in order to prevent the forementioned problems, for example, the edge-guided mode isolator[6] and the circulator with the non-reciprocal phase shifter[7]. The former, which is analogous to the edge-guided mode isolator at microwave frequencies, is unrealizable because the magnetooptic anisotropy of existing materials is too weak at optical frequencies. Because of the same reason, the latter gets too large to be realized, though the authors confirmed the function of the optical non-reciprocal phase shifter[8].

Here, we propose a new mode converter, which is applicable to a thin film optical isolator. An optical anisotropy is necessary in order to make the two cross-polarized modes degenerate in the mode converter. But, it is possible to take phase matching by 'the artificial anisotropic structure', which does not need any optical anisotropic crystal.

Approximate Treatment of the Artificial Anisotropic Structure

We propose a phase matched dielectric waveguide using the artificial anisotropic structure, Fig.1(a). The wave propagates in the z direction.

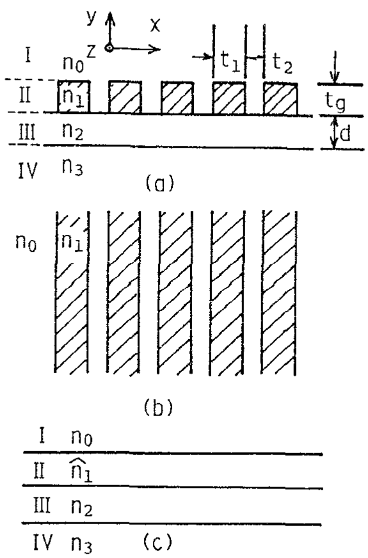

Fig.1 The artificial anisotropic waveguide (a), and its simplified models for an approximate analysis.

To analyze the characteristics of the proposed structure exactly is quite complicated. Let's, thus, consider it approximately by means of a simplified model, in which the concept of the artificial anisotropic structure is to be verified below.

In the periodically stratified dielectric structure with no y variation(Fig.1(c)), the eigenmodes are E and H modes with respect to x. The propagation constants of the lowest E and H modes in the z direction, β_e and β_h, respectively, are given as the solutions of the transcendental equation.

$$k_x \cdot \tan\left(\frac{k_x t_1}{2}\right) - \alpha \cdot \eta \cdot \tanh\left(\frac{\eta t_2}{2}\right) = 0 \qquad (1)$$

$$\beta^2 = n_1^2 k_0^2 - k_x^2 = n_0^2 k_0^2 + \eta^2, \quad k_0^2 = \omega^2 \varepsilon_0 \mu_0$$

$$\alpha = \begin{cases} \dfrac{n_1^2}{n_0^2} & \text{for E modes} \\ 1 & \text{for H modes} \end{cases}$$

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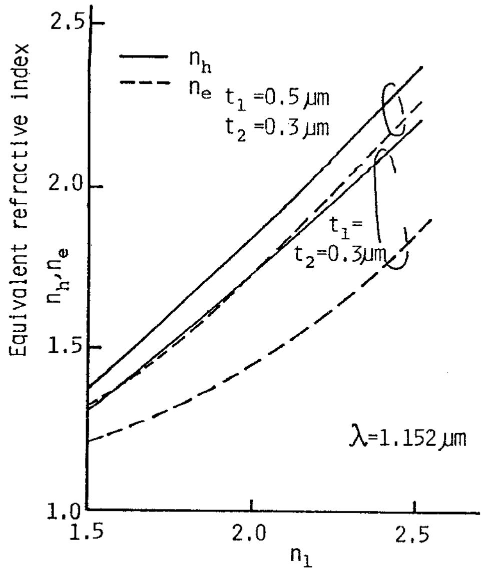

Fig.2 The equivalent refractive indices n_h and n_e as a function of n_1.

The equivalent refractive indices n_i (i=e,h) are defined for the two modes by

$$n_i=\beta_i/k_0 \qquad (i=e,h) \tag{2}$$

Fig.2 shows n_e and n_h as a function of the refractive index n_1, where n_0=1.0. In general, $n_h > n_e$. Thus, in the structure of Fig.1(a), the equivalent refractive indices of the region II for the E^x and E^y modes are different. After replacing the region II of the structure (a) by the uniform layer with refractive index n_e or n_h for the E^x or E^y mode, respectively, the three-dimensional structure, (a), becomes the two-dimensional one, (c). In this structure the refractive index of the region II, $\hat{n}_1$, varies by the different polarization as if it were an optical anisotropic crystal. This is referred to as the artificial anisotropic structure. The E^x and E^y modes in (a) are treated approximately as the TE and TM modes in (c). The propagation constants in the z direction, β, of the structure (c) are determined by the following set of equations.

$$\frac{k_y}{\alpha_2}\left\{\frac{\eta_3}{\alpha_3}\cos(k_y d)-\frac{k_y}{\alpha_2}\sin(k_y d)\right\}\left\{\frac{\eta_1}{\alpha_1}\cosh(\eta_1 t_g)+\frac{\eta_0}{\alpha_0}\sinh(\eta_1 t_g)\right\}+\frac{\eta_1}{\alpha_1}\left\{\frac{k_y}{\alpha_2}\cos(k_y d)+\frac{\eta_3}{\alpha_3}\sin(k_y d)\right\}\cdot\left\{\frac{\eta_1}{\alpha_1}\sinh(\eta_1 t_g)+\frac{\eta_0}{\alpha_0}\cosh(\eta_1 t_g)\right\}=0 \tag{3}$$

$$\beta^2=n_0^2k_0^2+\eta_0^2=\hat{n}_1^2k_0^2+\eta_1^2=n_2^2k_0^2-k_y^2=n_3^2k_0^2+\eta_3^2$$

$$\alpha_i=\begin{cases}1 & \text{for TE modes}\\ n_i^2 & \text{for TM modes}\end{cases} \qquad (i=0,1,2,3)$$

Fig.3 shows the difference of the propagation constants of the lowest TE and TM modes as a function of the film thickness of the region III as a parameter of n_1. Where,

$$\Delta\beta=(\beta^{TE}-\beta^{TM})/(\beta^{TE}+\beta^{TM}) \tag{4}$$

Δβ becomes zero when d=0.308μm for n_1=2.1, and when d=0.809μm for n_1=2.18, i.e., the two modes are degenerated in these waveguide parameters.

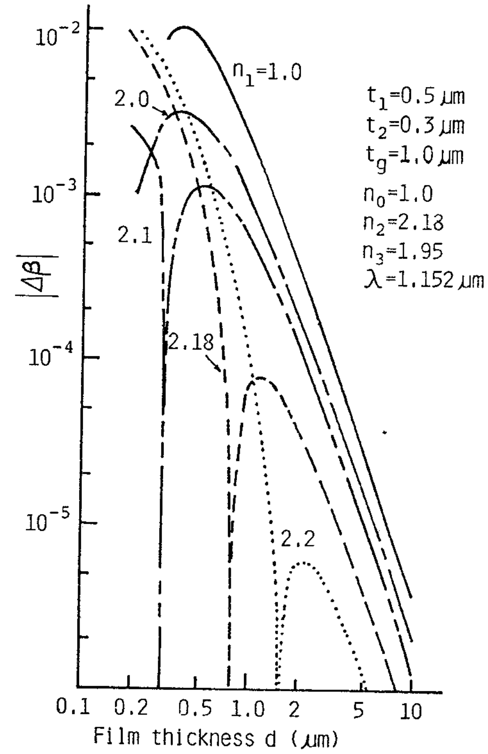

Fig.3 The difference of the propagation constants of the lowest TE and TM modes as a function of the film thickness d.

Now, let's consider the wave propagating along the x axis in the structure of Fig.1(a). In this case, the refractive index $\hat{n}_1$ is equal to n_h or n_e for the TE or TM modes, respectively. Since $n_h > n_e$, it is impossible to make the TE and TM modes of the same order phasematch.

Estimate of Mode Conversion

When the structure of Fig.1 contains a magnetooptic material, nonreciprocal mode conversion occurs. Here, we estimate the mode conversion in the structure of Fig.1(c) by using 'circuit-theory treatment'[9] after Yamamoto et al.

Let the normalized amplitudes of the TE and TM modes be denoted as $a^{TE}(z)$ and $a^{TM}(z)$. At z=l, $a^{TE}(l)$ and $a^{TM}(l)$ are related to the incident waves at z=0, $a^{TE}(0)$ and $a^{TM}(0)$, by means of the transmission matrix [T].

$$\begin{bmatrix} a^{TE}(l) \\ a^{TM}(l)\end{bmatrix}=\exp(-j\Phi)\,[T]\begin{bmatrix} a^{TE}(0) \\ a^{TM}(0)\end{bmatrix} \tag{5}$$

When the region III consists of the magnetooptic material which has the dielectric tensor

$$\varepsilon_0\begin{pmatrix}\varepsilon_{xx} & \varepsilon_{xy} & 0\\ \varepsilon_{xy}^* & \varepsilon_{yy} & 0\\ 0 & 0 & \varepsilon_{zz}\end{pmatrix} \tag{6}$$

the [T] matrix becomes as follows.

$$[T]=\begin{bmatrix}\cos\Theta-jP\sin\Theta & jQ\sin\Theta\\ jQ^*\sin\Theta & \cos\Theta+jP\sin\Theta\end{bmatrix} \tag{7}$$

where

$$P=\delta/k/\sqrt{1+(\delta/k)^2}\ ,\quad Q=-\alpha/\sqrt{1+(\delta/k)^2}$$
$$\Theta=\beta_m k\sqrt{1+(\delta/k)^2}\cdot l$$
$$\delta=(\beta^{TE}-\beta^{TM})/(\beta^{TE}+\beta^{TM})$$
$$k=|N_L|/\beta_m,\quad \beta_m=(\beta^{TE}+\beta^{TM})/2$$
$$\alpha=N_L/|N_L|,\quad \Phi=\beta_m l$$

and the overlap integral

$$N_L=\omega\varepsilon_0\int\varepsilon_{xy}^{*}\,E_x^{TE*}\cdot E_y^{TM}\,dy$$

β^{TE} and β^{TM} are calculated in the preceding section. The off-diagonal terms in the [T] matrix represent the TE-TM mode conversion. The maximum power conversion is

$$F=|Q|^2=1/\sqrt{1+(\delta/k)^2} \qquad (8)$$

at $\Theta=\pi/2,\ 3\pi/2,\cdots$. The shortest propagation length for the maximum power conversion, L, is

$$L=\pi/2\beta_m k\sqrt{1+(\delta/k)^2} \qquad (9)$$

Figs.4(a) and (b) show F and L as a function of d. The assumed dielectric tensor components of the region III are $\varepsilon_{xx}=\varepsilon_{yy}=\varepsilon_{zz}=(2.18)^2$ and $\varepsilon_{xy}=-j3.4\ 10^{-4}$[3], which corresponds to the garnet $(LaY)_3Ga_{0.33}Fe_{4.67}O_{12}$ magnetized in the z direction. And the wavelength is 1.152μm.

Complete mode conversion (F=1) is obtained when the two modes are degenerated. However, only 50% mode conversion is required for the nonreciprocal circuit of optical isolator. In such cases, just slight phase mismatch are to be allowed. Comparing Figs.4(a) and (b), it is clear that the larger n_1 gets the wider the extent of the usable film thickness d.

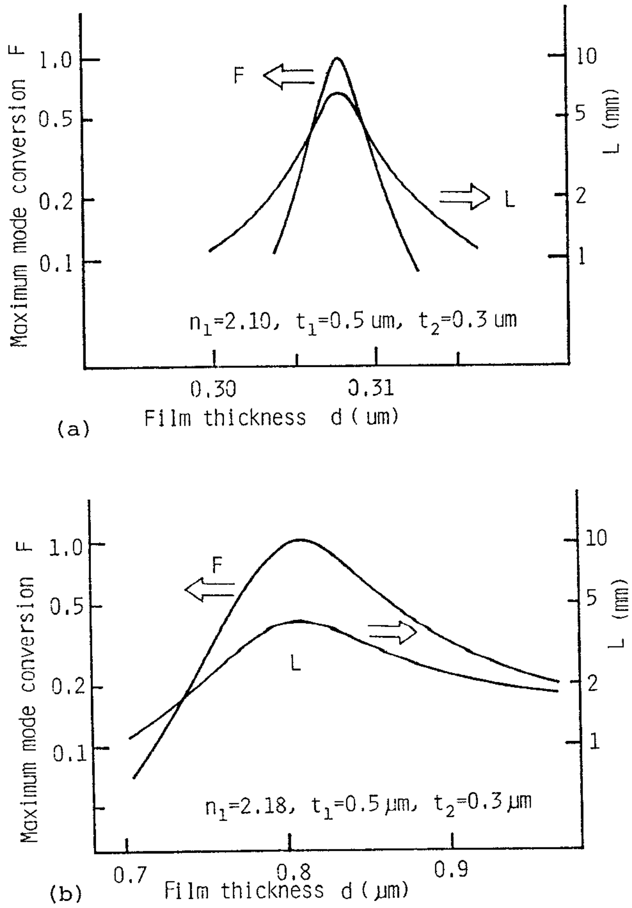

Fig.4 The maximum power conversion, F, and the shortest propagation length for the maximum power conversion, L. n_1=1.0, n_3=1.95, t_g=1.0μm, and λ=1.152μm.

Conclusion

We proposed a new phase matching technique between the two cross-polarized waves in the dielectric waveguide, i.e., the concept of the artificial anisotropic structure. Using this technique, nonreciprocal mode converters become realizable more easily, because they do not need any other anisotropic material than the magnetooptic one like a kind of garnet.

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