Advances in Magneto-Optics, Proc. Int. Symp. Magneto-Optics, J. Magn. Soc. Jpn. Vol. 11, Supplement, No. S1 (1987) 381–384.

NON RECIPROCAL PHASE MATCHING IN FOUR-LAYER MAGNETOOPTICAL WAVEGUIDES

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ABSTRACT

Non reciprocal single-mode conversion $TE_0 \rightarrow TM_0$ in a four-layer magnetooptical waveguide has been studied as a function of the external applied magnetic field.

I. INTRODUCTION

Some devices used in integrated optics are based on single-mode conversion (1) and require non-reciprocity along the light propagation direction (isolators, circulators, etc.). Although this non-reciprocal single-mode conversion can be obtained in waveguides where the active layer is placed between two layers of isotropic material. The use of an extra layer placed between the substrate and the active film, would allou to work with thicker guiding layers (2).

Initially, we present in this work a detailed calculation of the single mode propagation together with non-reciprocal mode conversion in an optical system consisting of two parallel isotropic dielectric slab waveguides coupled by means of two thin layers (one made of magnetooptical material and the second made of isotropic material), inserted between them.

Finally, the non-reciprocal single mode conversion has been analyzed as a function of the direction of the applied magnetic field, for a material such as Tb:YIG and for wavelenghts of 1.51µm.

II. WAVEGUIDE STRUCTURE

We consider a waveguide structure (Figure 1) formed by two thin films grown by LPE on an isotropic substrate (GGG). The film on top is made of magnetooptic material ($Y_{3-x}\ RE_x\ Fe_{5-y}\ RE_y\ O_{12}$) and the intermediate layer is made of an isotropic material.

In our study, the propagation direction has been taken as "x" axis. We have assumed that the fields do not change along the "y" axis ($\partial/\partial y = 0$).

The magnetooptic material is characterized by a permitivity tensor ε(3). This tensor can be expressed as a function of the material's magnetooptical coefficients and the magnitude and direction of the magnetization (Figure 2). Table I shows the values of the magnetooptical coefficients used in this work.

TABLE I. MAGNETOOPTICAL COEFFICIENTS OF THE ACTIVE LAYER

$f_1^e\ M$	$f_{12}\ M^2$	$f_{44}\ M^2$	$\Delta f\ M^2$ (M=Magnetization)
-5.19	1	1.33	-0.42 ($\times 10^{-4}$)

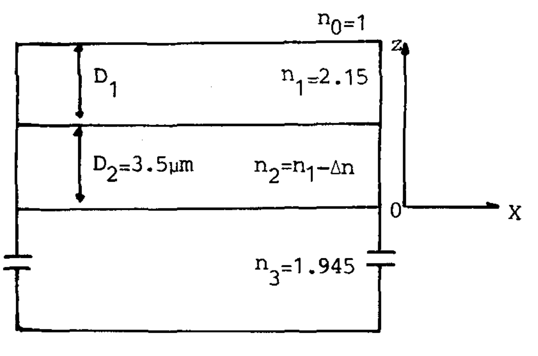

Fig. 1.- Waveguide structure

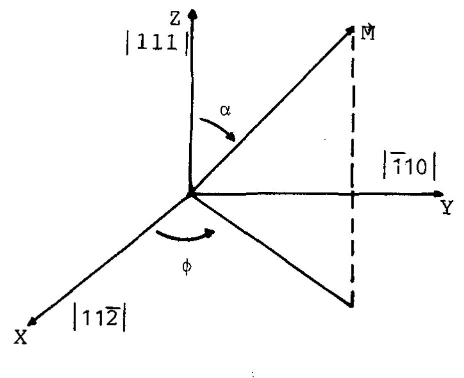

Fig. 2.- Coordinate system

III. LIGHT PROPAGATION IN A FOUR-LAYER MAGNETOOPTIC WAVEGUIDE

To solve the problem of light propagation in a M.O. film, a perturbation method has been used. If we let the ε_{xy} and ε_{yz} terms of the permitivity tensor be zero, then the propagation modes are TE or TM. This case is closely achieved by means of an equatorial magnetization.

The TE mode is the same as for an isotropic film with the ε_{yy} permitivity (4). The TM propagation modes when there is propagation only in the active layer, are given by:

$$\frac{\varepsilon_{zz} \cdot b^{TM}}{\Delta\varepsilon} \operatorname{tg} (b^{TM} D_1 - \phi_{10} - m\Pi) = \frac{p_2}{n_2^2} \coth (p_2 D_2 + \psi) + \frac{\operatorname{Im}(\varepsilon_{xz})}{\Delta\varepsilon} \beta \tag{1}$$

where:

$$\Delta\varepsilon = \varepsilon_{xx}\, \varepsilon_{yy} - \varepsilon_{xz}\, \varepsilon_{zx} \tag{2}$$

$$\beta^2 - p_i^2 = (K_0 n_i)^2 \tag{3}$$

$$(b^{TM})^2 = \left(\frac{\varepsilon_{xz} - \varepsilon_{zx}}{2\, \varepsilon_{zz}}\right)^2 \beta^2 + \frac{\Delta\varepsilon}{\varepsilon_{zz}^2} (K_0^2 \varepsilon_{zz} - \beta^2) \tag{4}$$

$$\phi_{10} = \operatorname{tg}^{-1} \left(\frac{\Delta\varepsilon p_0 - n_0^2\, \varepsilon_{xz}\, \beta}{n_0^2\, \varepsilon_{zz}\, b^{TM}}\right) \tag{5}$$

$$\psi = \operatorname{th}^{-1} \left(\frac{n_3^2\, p_2}{n_2^2\, p_3}\right) \tag{6}$$

If the magnetization is not equatorial, the off-diagonal components can be not negligeable and a TE-TM coupling process takes place. Due to the fact that this coupling process is only important for modes of the same order, we will use a 2-fundamental mode, approximation.

When mode-conversion efficiency depends on the propagation direction ($\beta>0$, forward modes and $\beta < 0$ backward modes), it is called non-reciprocal.

By using the well known relation between coupled modes, and using a perturbation method introduced by Yariv (5), mode conversion can be characterized by the expressions:

$$T_{TE}^{TM} = \frac{K^2}{\Delta^2 + K^2} \sin^2 \sqrt{\Delta^2 + K^2}\; x \tag{7}$$

$$L_c = \frac{\Pi}{2\sqrt{\Delta^2 + K^2}} \tag{8}$$

where:

T_{TE}^{TM} = TE - TM conversion rate

L_c = device lenght necessary to achieve maximal conversion rate

$K^2 = K_{TE}^{TM} \times K_{TM}^{TE}$ coupling coefficient

$$K_{TE}^{TM} = -\frac{i}{4} \beta^{TM} \frac{\varepsilon_{yz}}{\varepsilon_r} \int_{D_2}^{D_1+D_2} h_y(z) e_y(z) dz - \frac{1}{4} \frac{\varepsilon_{yx}}{\varepsilon_r} \int_{D_2}^{D_1+D_2} \frac{\partial h_y(z)}{\partial z} e_y(z) dz \tag{9}$$

$$K_{TM}^{TE} = -\frac{i}{4} \beta^{TE} \frac{\varepsilon_{zy}}{\varepsilon_r} \int_{D_2}^{D_1+D_2} h_y(z) e_y(z) dz - \frac{1}{4} \frac{\varepsilon_{xy}}{\varepsilon_r} \int_{D_2}^{D_1+D_2} \frac{\partial e_y(z)}{\partial z} h_y(z) dz \tag{10}$$

$\Delta = |\beta^{TM} - \beta^{TE}|$ phase matching

IV. SINGLE MODE CONVERSION

In many optical devices, it is important for practical uses, to have propagation of only one mode of each kind. For typical slab wavequides consisting of a thin film grown onto a substrate, there will be single mode propagation only for layer widths thiner than 1μm.

One way to perform single mode propagation in better conditions is to use double (2) or triple (6) layers grown onto the substrate, with the active layer on the top side. In this case, only one mode of each kind will propagate through the top layer, meanwhile the intermediate layer will serve to propagate a number of different modes which will attenuate strongly if the layer has a high absorption at the working wavelength.

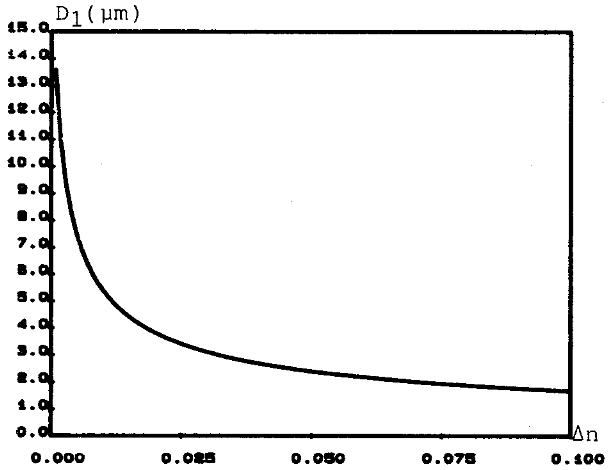

Fig. 3. Critical width for TE_1 propagation in the active layer in function of $\Delta n=n_1-n_2$ (n_2=refraction index of the layer below the active layer)

The single mode propagation condition will define a thickness interval for the active layer, limited by the critical width for TE_0 propagation and that one for TE_1 propagation. It can be shown that this interval is mainly a function of the difference between the refraction indexes of the active layer and the layer below it ($\Delta n = n_1-n_2$). Figure 3 shows the value of the active layer's critical thickness for TE_1 propagation as a function of Δn in a four-layer waveguide (n_2 = refraction index of the intermediate layer) and a three-layer waveguide (n_2 = refraction index of the substrate).

Although the curve is identical for both cases, it is to be noticed that in a three layer magnetooptical waveguide consisting of substituted YIG grown onto a GGG substrate, there is no way to have a Δn smaller than 0.2 (critical width=1μm), meanwhile in a four-layer waveguide it is possible to have a Δn as small as wished by means of the intermediate layer, and thereupon to achieve higher values of the critical width.

For the rest of our study the "reasonable" value Δn = 0,002 will be used.

V. NON RECIPROCAL MODE CONVERSION

The effect of inverting the propagation direction in a non-reciprocal waveguide, is the same as if the magnetization's sign was changed.

As it is well known, the components of the permitivity tensor in these materials are such that:

$$\varepsilon_{ij}(m) = \begin{cases} \varepsilon_{ij}(-m) & \text{if } i=j \\ \varepsilon^*_{ij}(-m) & \text{if } i\neq j \end{cases}$$

thereupon, non-reciprocity will show in those parameters where off-diagonal elements of ε are included.

For practical uses, if the "non-reciprocity" reached through coupling coefficients and phase-matching is not very high (3), the best way to achieve it would be by means of the device's length, which for some given value could maximize one conversion rate and minimize the other. The steps to follow would be:

a) Optimization of the maximal conversion rate for direct propagation.

b) Calculation of the device's lenght giving maximal non-receprocity.

The waveguide we are going to analyse has the following parameters:

$n_0 = 1$

$n_1 = 2.15$

$n_2 = 2.148$

$n_3 = 1.945$

and the magnetooptical coefficients given in Table I. We have only to establish the direction of the magnetization, the width of the active layer and the device's length.

Figure 4 shows the conversion rate for all forward and backward waves as a function of the device's length and for an active layer's thickness of 6μm. The magnetic configuration is given by the angles: $\alpha = 10°$

$\phi = 0°$

The non-reciprocal conversion rate has been calculated as well for a three-layer guide ($\Delta n=0$, $D_2=0$), assuming the same parameters as used for the four-layer configuration. Our results show a small conversion rate (∿20%) and scarce non-reciprocity. As we are here mainly interested in single-mode effects, a three-layer configuration would imply values $D_1 < 1\mu m$ of the active layer's width. In this case, the non-reciprocal conversion rate would be even lower.

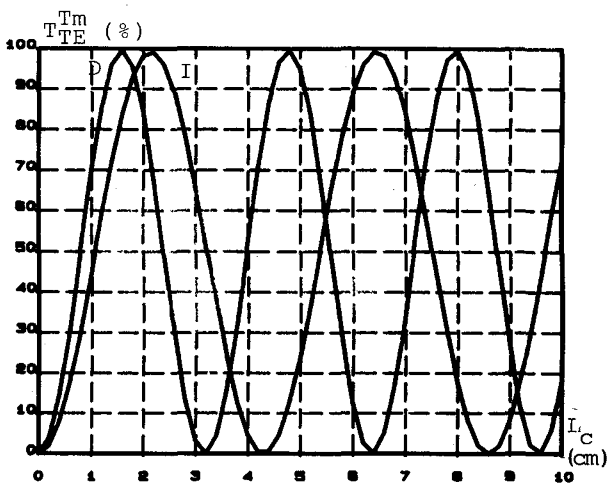

Fig. 4.- Conversion efficiency rate for direct and inverse propagation as a function of device's width for $\alpha=10°$, $\phi=0°$ and $D_1 = 6\mu m$.

VI. CONCLUSIONS

Non reciprocal single-mode TE_0-TM_0 conversion in a four-layer magnetooptical waveguide has been analysed. There are mainly three parameters to optimize: single-mode propagation, conversion efficiency rate and non-reciprocity. This can be done mainly by means of Δn (difference between the refractive indexes of the active and intermediate layer), D_1 (active layer's width) and the magnetization's direction. A waveguide structure is suggested allowing to have non reciprocal single-mode conversion ($\lambda=1.51\mu m$) with a conversion efficiency rate of 80% and 10% for forward and backward propagation respectively and for a device's lenght of 2.9 cm.

REFERENCES

1. A. Shibukawa et al., Appl. Optics 20, 2444 (1981).
2. R. Wolfe et at. Appl. Phys. Lett. 46, 817 (1985).
3. M. Torfeh et al, Physica 89 B, 255 (1977)
4. F. Canal and J. Hernández, Annual Meeting of the Optical Society of America, Seattle, October 1986.
5. A. Yariv, IEEE Journal of Quantum Electronics QE-9, 919 (1973).
6. R. Wolfe et al. Appl. Phys. Lett. 48, 508 (1986).