

Nonlinear cut-off integrated optical isolator

K. GNIADÉK*

Ecology and Management University, 14 Wawelska Str., 02–061 Warsaw, Poland
Faculty of Physics, Warsaw University of Technology, 78 Koszykowa Str., 00–662 Warsaw, Poland

The paper presents a concept of an integrated isolator which operation combines the magneto-optic nonreciprocity and nonlinear effects. The isolator is based on nonreciprocal cut-off of TM modes in magneto-optical planar structure where one layer (e.g. top one) is nonlinear. The power dependence of the propagation constants in such configuration allows for easy control of the nonreciprocal behaviour of the counterpropagating TM modes and nonreciprocal cut-off thickness.

Keywords: magneto-optics, nonlinear waveguides, integrated isolators.

1. Introduction

The nonreciprocal devices such as isolators and circulators are suitable for stabilization of the semiconductor-laser operation to avoid self-oscillation of the laser due to reflection in the communication systems. Most proposals of the waveguide type isolators are based on nonreciprocal TE-TM mode conversion [1–3]. In order to achieve the efficient TE-TM conversion, the precise phase matching between the interacting modes is required. The latter can be obtained by precise orienting of the materials optical axis and by accurate controlling of the film thickness. These requirements are difficult to fulfil in practice. The other concept of an optical isolator is based on nonreciprocal phase shift of TM modes in magneto-optical waveguide [4–8]. It was shown that propagation constant of the TM mode is different for propagation in the opposite direction if the magnetization is adjusted in parallel to the film plane and perpendicularly to the direction of mode propagation. Such a structure is called as transversal or Voigt configuration. It is well known that the modes in the Voigt configuration can be separated into TE $[E_y, H_x, H_z]$ and TM $[H_y, E_x, E_z]$ polarizations. In transversal configuration, the TE and TM modes are not coupled. TE waves do not interact with the applied magnetic field. The advantage of this concept arises from fact that only one polarization, namely TM is involved and therefore the phase matching is not needed anymore.

The aim of this paper is to present the concept of an integrated optical isolator based on a new configuration of the magneto-optical layered structure in which one medium (e.g. top layer) is nonlinear. Nonlinear optical waveguides exhibit a number of interesting properties which have been studied extensively (see for example references in review papers [9–10]) because of their potential applications in

all-optical signal processing. Introduction of the nonlinear material into magneto-optical waveguide gives an additional “degree of freedom”, namely the power of the guided wave. The power dependence of the propagation constant allows for control of the nonreciprocal behaviour of the counterpropagating TM modes. This allows for applying the magneto-optical-nonlinear waveguides in a new class of integrated devices which functions combine the magneto-optical and nonlinear effects. As an example, such a device can be used as nonreciprocal limiter of the guided power flow. Another possibility is the intensity-controlled integrated isolator based on the magneto-optical directional coupler [11]. In such a structure, the nonlinearity acts on propagation constants of the counterpropagating TM modes, modifying the coupling condition. Therefore the transfer efficiency can be optimised, e.g., in backward direction and reduced for the forward propagation direction.

2. Dispersion relation for TM modes

The guiding structure considered in this paper consists of three layers, i.e., the magneto-optical substrate, linear non-magnetic film, and nonlinear layer (here the top one). The external magnetic field H_0 is applied in parallel to the film plane and perpendicularly to the direction of propagation, along the z -axis (forming so-called Voigt configuration). Neglecting losses, the corresponding dielectric tensor of magneto-optical (gyrotropic) material has the form

$$\epsilon^{MO} = \begin{pmatrix} \epsilon_x & 0 & i\delta \\ 0 & \epsilon_y & 0 \\ -i\delta & 0 & \epsilon_z \end{pmatrix}. \quad (1)$$

The nondiagonal elements δ are related to the specific Faraday rotation angle θ_F by $\delta = \theta_F \sqrt{\epsilon_z} \lambda / \pi$ [6].

The modes in the Voigt configuration can be separated into TE $[E_y, H_x, H_z]$ and TM $[H_y, E_x, E_z]$ polarizations. The

* e-mail: gniadek@if.pw.edu.pl

TE and TM modes are not coupled. Properties of the TE modes do not depend on the propagation direction. We consider only TM modes because the TM modes are nonreciprocal in Voigt configuration. For simplicity, the magneto-optic medium is assumed to be isotropic $\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_s$. We suppose that nonlinear cladding is Kerr-type and isotropic, and nonlinear dielectric sub-tensor for the TM waves is given by

$$\varepsilon^{NL} = \begin{pmatrix} \varepsilon_{xx} & 0 \\ 0 & \varepsilon_{zz} \end{pmatrix}, \quad (2)$$

where elements ε_{xx} and ε_{zz} depend on the local intensity and we assume that (for electrostrictive or thermal nonlinearity)

$$\varepsilon_{xx} = \varepsilon_{zz} = \varepsilon^{NL} = \varepsilon_L + \alpha(|E_x|^2 + |E_z|^2), \quad (3)$$

where ε_L is the linear part of the dielectric permittivity and α is the nonlinear coefficient.

The electric and magnetic field vectors for TM waves propagating along z -axis with the angular frequency ω and the propagation constant β are written as

$$\begin{aligned} \vec{E}(x, z) &= [E_x(x)\vec{i}_x + E_z(x)\vec{i}_z] \exp[i(\beta z - \omega t)], \\ \vec{H}(x, z) &= H_y(x)\vec{i}_y \exp[i(\beta z - \omega t)]. \end{aligned} \quad (4)$$

Assuming a decaying field in the magneto-optic substrate, and taking into account the conservation law for the nonlinear medium in a form [12]

$$|E_x|^2 \left[-2(k_0/\beta)^2 \eta^2 + 3\eta - 1 \right] - |E_z|^2 (\eta + 1) = \text{const}, \quad (5)$$

and applying the boundary condition at the film-substrate and film-cover interfaces one obtains the relation

$$\begin{aligned} k_0 d \gamma_f &= \arctg \left(\frac{n_f}{n_s} \right)^2 \frac{\varepsilon_s \gamma_s - N \delta}{\varepsilon_s \gamma_f} \\ &- \arctg \left(\frac{\varepsilon_f}{\varepsilon_c \eta} \sqrt{\frac{(3\eta - 1)(N^2 - \eta^{(NL)2})}{(\eta + 1)(n_f^2 - N^2)}} \right), \end{aligned} \quad (6)$$

where $N = \beta/k$, $\gamma_f = \sqrt{n_f^2 - N^2}$, $\gamma_s = \sqrt{N^2 - n_s^2}$, $n_s = \sqrt{(\varepsilon_s^2 - \delta^2)}/\varepsilon_s$ is the effective index of refraction of magneto-optic medium, $\eta = \varepsilon^{NL}/\varepsilon_L = 1 + (\alpha/\varepsilon_c) (|E_{xx}|^2 + |E_{zz}|^2)$ is the normalized boundary value of the nonlinear permittivity (local power density).

Equation (6) is the dispersion relation of TM modes which determines the propagation constant β . Due to the off-diagonal elements δ in dielectric tensor (1), a term proportional to β exists in dispersion Eq. (6). Thus, the absolute value of the propagation constant is different for prop-

agation in opposite directions (depending on the sign of β). Note that a change of the sign of δ (by reversing of the direction of external magnetic field) has the same effect as the change of the sign of β . Assuming that the minimum value of the propagation constant $\beta_{\min} = kn_s$ and inserting it into Eq. (6) one can obtain the cut-off thicknesses d_c^+ and d_c^- for the forward and the backward direction of propagation, respectively. For the isolator applications, it is important to achieve a large difference between the cut-off thicknesses d_c^+ and d_c^- . It results also from dispersion Eq. (6) that propagation constants (and cut-off thicknesses d_c^+ and d_c^-) depend on the guided power flow (via power density η at the film-cover interface). Note, that the limit $\eta \rightarrow 1$ in Eq. (6) yields to the dispersion relation for linear magneto-optic waveguide.

3. Numerical results

The numerical results were calculated for the following parameters: $\varepsilon_s = 5.1$, $\varepsilon_f = 5.5$, $\varepsilon_L = 4.2$, and $\lambda = 1.15 \mu\text{m}$. To emphasize the effect of the nonreciprocity, the values of δ were chosen being two orders of magnitude larger than typical value of δ .

In magneto-optic-nonlinear waveguide, the nonreciprocal characteristics are affected by the intensity of the guided wave. The difference between the effective indices $\Delta N = N^- - N^+ = (\beta^- - \beta^+)/k$ for the backward and the forward propagation of TM_0 mode versus boundary value of nonlinear permittivity $\eta = \varepsilon^{NL}/\varepsilon_L$ in self focusing ($\alpha > 0$) cladding is demonstrated in Fig. 1. Note that when reaches value of 1.38 then $\Delta N = \Delta\beta/k$ changes its sign. It means that at total power flow, determined by this value of η , the nonreciprocal phase shift disappears. The difference propagation constants $\Delta\beta = \beta^- - \beta^+$ versus boundary value of nonlinear permittivity $\eta = \varepsilon^{NL}/\varepsilon_L$ in self focusing cover for the different values of η the similarity $p = n_s/n_f$ of refractive indices of film and magneto-optic

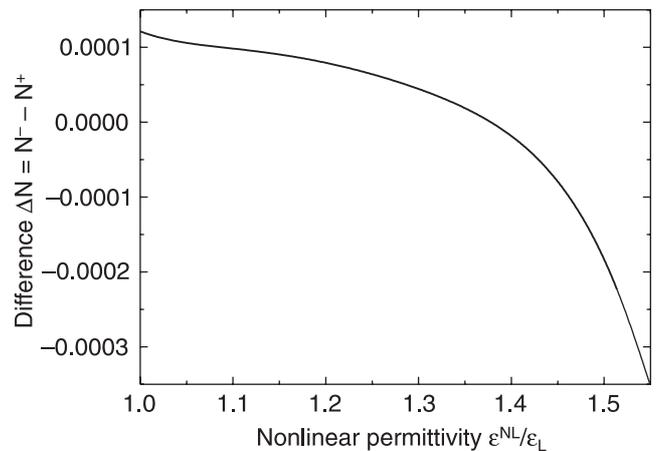


Fig. 1. Difference between the effective indices $\Delta N = N^- - N^+ = (\beta^- - \beta^+)/k$ for the backward and the forward propagation of TM_0 mode versus the nonlinear permittivity $\varepsilon^{NL}/\varepsilon_L$ in the self focusing nonlinear cover.

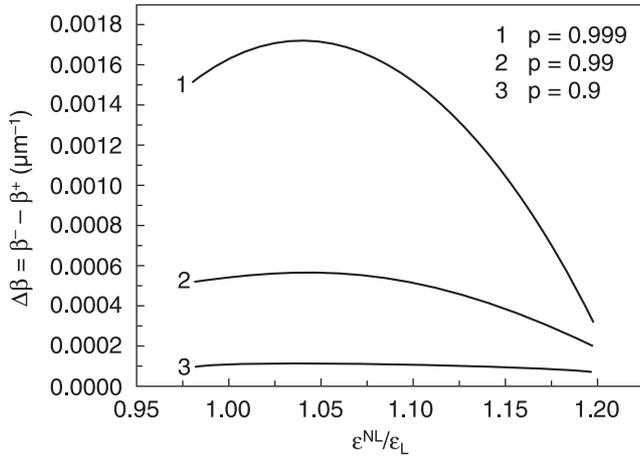


Fig. 2. Difference between the propagation constants $\Delta\beta = \beta^- - \beta^+$ versus the nonlinear permittivity ϵ^{NL}/ϵ_L at the interface film – self focusing nonlinear cover for different values of the similarity parameter $p = n_s/n_f$.

substrate are presented in Fig. 2. The largest difference $\beta^{(-)} - \beta^{(+)}$ occurs for the largest values of the similarity parameter p . Figures 3 and 4 show variation of the normalized cut-off thickness of the forward and the backward direction of propagation with η for the case of self defocusing and focusing cladding, respectively. The normalized cut-off thicknesses $w^{(+)}$ and $w^{(-)}$ increase when η decreases from the linear limit $\eta = 1$. They reach the maximum at $\eta = 0.63$ and, subsequently, decay when η tends to the threshold value. In the case of the self-focusing cover, the values of cut-off thicknesses decrease with increase in the boundary value of the normalized nonlinear permittivity η . Note that the difference between the cut-off thickness for the forward and the backward propagation does not depend on the boundary values of the power density. The optimisation problem for cut-off isolator in linear case was analysed in Ref. 6.

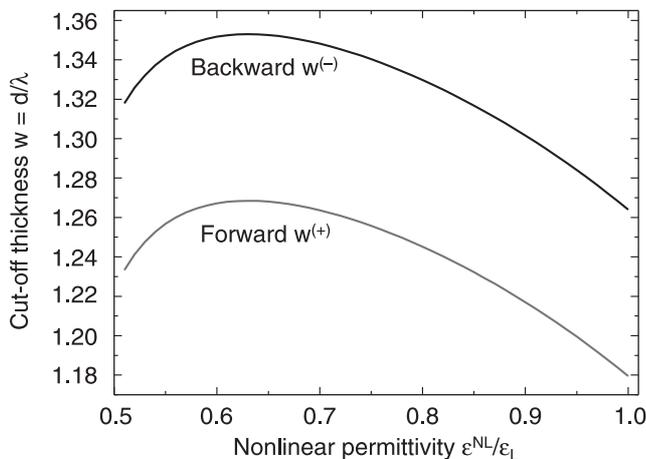


Fig. 3. Normalized cut-off thicknesses for the forward w^+ and the backward w^- propagation of TM_0 mode versus the nonlinear permittivity ϵ^{NL}/ϵ_L at the interface film – self defocusing nonlinear cover ($\alpha < 0$).

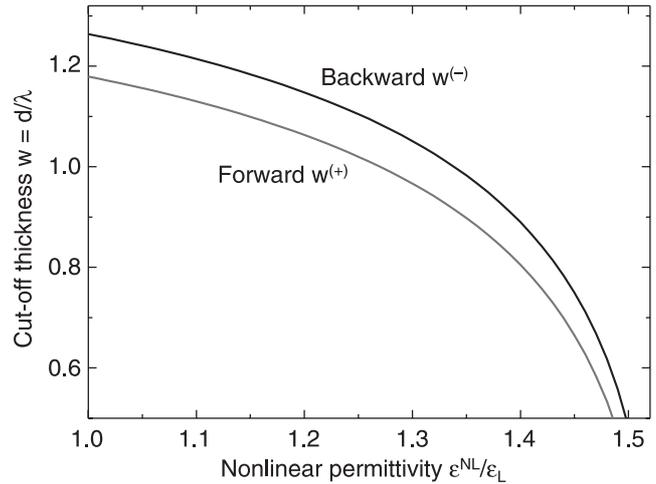


Fig. 4. Normalized cut-off thicknesses for the forward w^+ and the backward w^- propagation of TM_0 mode versus the nonlinear permittivity ϵ^{NL}/ϵ_L at the interface film – self focusing nonlinear cover ($\alpha > 0$).

4. Conclusions

The concept of an integrated isolator, which operation combines the magneto-optic nonreciprocity and nonlinear effects was presented. The isolator is based on nonreciprocal cut-off of TM modes in magneto-optical planar structure composed of the linear thin film sandwiched between magneto-optic substrate and Kerr-type nonlinear cladding. The magnetization is adjusted in parallel to the film plane and perpendicularly to the direction of propagation. The theoretical and numerical analyses of the nonreciprocal behaviour of the TM modes propagating in the opposite directions have been carried out. Thanks to the conservation law for TM modes in nonlinear waveguide, the dispersion relation without knowledge of the nonlinear field has been derived. The nonreciprocal phase shift of the counter-propagating TM waves in such a structure is sensitive to the power flow in the guide. The cut-off thicknesses for the forward and the backward propagation are sensitive to the boundary value of the local intensity and consequently depend on the total power flow. If the light power reaches the magnitude for which the thickness of the waveguide becomes the cut-off value for the forward propagation, then only the reverse travelling is possible. Thus, the structure acts as an intensity controlled isolator for TM waves. The proposed magneto-optic-nonlinear waveguide structure can find its potential application in production of other integrated devices which operations combine the magneto-optic and nonlinear effects.

References

1. J. Warner, "Faraday optical isolator/gyrator design in planar dielectric", *IEEE Trans. Microwave Theory Tech.* MTT **21**, 769 (1973).

2. H. Hemme, H. Dotsch, and H.P. Menzler, "Optical isolator based on mode conversion in magnetic garnet films", *Appl. Opt.* **26**, 3811–3817 (1987).
3. K. Ando, "Waveguide optical isolator: a new design", *Appl. Opt.* **30**, 1080–1084 (1991).
4. Ch.L. Chen and A. Kumarswami, "Nonreciprocal TM-mode thin-film phase shifters", *Appl. Opt.* **25**, 3664–3670 (1986).
5. I.A. Zenteno, "Design of a magneto-optic slab isolator for integrated optics", *Opt. Lett.* **12**, 657–659 (1987).
6. H. Hemme, H. Dotsch, and P. Hertel, "Integrated optical isolator based on nonreciprocal-mode cut-off", *Appl. Opt.* **29**, 2741–2744 (1990).
7. A. Erdmann, P. Hertel, and H. Dotsch, "Nonreciprocal coupling effects in gyrotropic waveguide structures", *Optical and Quant. Electron.* **26**, 949–955 (1994).
8. K. Gniadek, "TM waves in magneto-optic-nonlinear waveguide", *Optica Appl.* **24**, 281–285 (1994).
9. D. Mihalache, M. Bertolotti, and C. Siglia, "Nonlinear wave propagation in planar structures", in *Progress in Optics*, Vol. 27, pp. 229, North Holland, Amsterdam, 1989.
10. N. Akhmediev, in *Modern Problems in Condensed Matter Sciences*, Vol. 29, pp. 289, North Holland, Amsterdam, 1991.
11. K. Gniadek, "Intensity-controlled nonreciprocal coupler", *Optica Appl.* **26**, 381–390 (1996).
12. K. Gniadek and M. Rusek, "Analysis of TM-polarized nonlinear guided waves based on a conservation law", in *Technical Digest on Nonlinear Wave Phenomena*, Vol. 25, pp. 100, Optical Society of America, Washington, 1991.