# OPTIMIZED NONRECIPROCAL RIB WAVEGUIDES FOR INTEGRATED MAGNETO-OPTIC ISOLATORS

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## ABSTRACT

Garnet films of composition $(Lu,Bi)_3(Fe,Ga,Al)_5O_{12}$ and $(Tm,Bi)_3(Fe,Ga)_5O_{12}$ are grown by liquid-phase epitaxy on [111]-oriented substrates of gadolinium gallium garnet. Ferrimagnetic films with positive or negative Faraday-rotation as well as paramagnetic films with negligible Faraday-rotation are produced by variations of the rare earth ion substitutions. The temperature dependence of Faraday-rotation is fitted with a molecular field model. Optical rib waveguides in single and double layer garnet films with different Faraday-rotations are realized. The nonreciprocal phase shift of the $TM_0$-Mode is studied both theoretically and experimentally at a wavelength of 1.3 $\mu$m. Results show that the maximum nonreciprocal effect at room temperature of double layer films with opposite Faraday-rotation is 1.6 times as large as that of comparable single layer waveguides. But, because of the large temperature dependence of the Faraday-rotation of the positive rotating films, these waveguides show a large temperature dependence of the nonreciprocal phase shift. This problem can be avoided if the positive rotating layer is replaced by a paramagnetic layer. Agreement between calculations and measurements is excellent.

## INTRODUCTION

Magneto-optic isolators play an important role in optical communication technique. They are used to protect the semiconductor lasers from reflected light. At present only bulk isolators are available. To realize cheap integrated optical isolators, magnetic garnet films can be used. They combine low absorption with high Faraday-rotation in the near infrared. The Faraday-rotation, which is the basis of the nonreciprocal effects, can be enhanced by bismuth substitution. Various kinds of optical isolators have been proposed [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Some promising concepts of integrated optical isolators and circulators rely on the nonreciprocal phase shift of TM modes [11, 12], which is the difference $\Delta\beta = \beta_{\rm fw} - \beta_{\rm bw}$ between the forward and backward propagation constants $\beta_{\rm fw}$ and $\beta_{\rm bw}$ of TM modes, respectively. The device length of such isolators is inversely proportional to this effect so that an enhancement is desirable. For this purpose double layer garnet films with opposite Faraday-rotation are suitable [13]. In this paper it is shown, how the temperature dependence and the absolute value of $\Delta\beta$ can be optimized by choosing a proper geometry of the waveguides.

## NONRECIPROCAL RIB WAVEGUIDES

The following analysis is performed for the basic rib geometry sketched in Fig. 1. Mode propagation is assumed along the $z$ axis and the magnetization $\boldsymbol{M}$ is adjusted in the film plane transversely to the propagation direction. Neglecting optical damping, the dielectric tensor of the magneto-optic films can be written as

$$\hat{\epsilon} = \begin{pmatrix} n^2 & 0 & \mathrm{i}\xi \\ 0 & n^2 & 0 \\ -\mathrm{i}\xi & 0 & n^2 \end{pmatrix}. \tag{1}$$

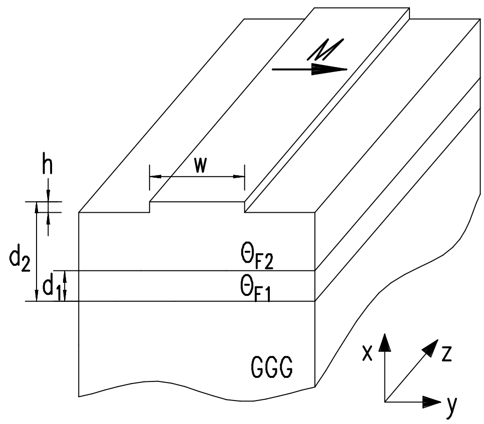


Figure 1: Basic geometry of the rib waveguide.

$n$ is the isotropic refractive index and $\xi$ represents the magneto-optic effect. It is related to the Faraday-rotation $\Theta_{\mathrm{F}}$ by

$$\xi \approx 2n\Theta_{\mathrm{F}}/k_0, \tag{2}$$

where $k_0$ is the vacuum wave number.

Using Maxwell's equations, one can derive the following partial differential equations describing quasi TE and quasi TM modes, respectively [14] :

$$(-\partial_x^2 - \partial_y^2 + \beta^2)E_y = \epsilon k_0^2 E_y \ , \tag{3}$$

$$(-\epsilon\partial_x\epsilon^{-1}\partial_x - \partial_y^2 + \beta^2 - \epsilon\beta(\partial_x\frac{\xi}{\epsilon^2}))H_y = \epsilon k_0^2 H_y \tag{4}$$

with $\epsilon = n^2$. The TM mode equation contains a term linear in $\beta$ which causes the nonreciprocal effect. TE modes behave reciprocal.

These equations can be solved using a finite difference [14] or a finite element method [15] . Since the term $\epsilon\beta(\partial_x\xi/\epsilon^2)$ can be regarded as a small perturbation, we first solve the unperturbed mode equation utilizing a finite element method [16] . Then perturbation theory yields

$$\Delta\beta = \frac{\iint |H_y|^2(\partial_x\frac{\xi}{\epsilon^2})dxdy}{\iint \epsilon^{-1}|H_y|^2 dxdy} \tag{5}$$

for the nonreciprocal phase shift [17] .

To achieve a large $|\Delta\beta|$, double layer garnet films with opposite Faraday-rotation are prepared where the boundary between layers is located close to the maximum of $|H_y|^2$ [13]. Double layer waveguides with a positive rotating bottom layer and a negative rotating top layer show the highest differential nonreciprocal phase shift [18]. To reverse the sign of the Faraday-rotation from negative to positive, gallium is substituted onto the tetrahedral sites of the garnet until the magnetization of the octahedral sites dominates. Thus a compensation wall is established separating the layers with $\Theta_{\mathrm{F}}^- < 0$ and $\Theta_{\mathrm{F}}^+ > 0$. This procedure always results in $|\Theta_{\mathrm{F}}^-| > |\Theta_{\mathrm{F}}^+|$, see Ref. [13].

The temperature dependence of the Faraday-rotation of the garnet films investigated is displayed in Fig. 2. The composition and the material parameters of both samples are given in Table 1. Due to the large temperature dependence of the positive Faraday-rotation such films are not suitable for the realization of a device. Therefore, we use a paramagnetic bottom layer (0.18 $\mu$m) with negligible Faraday-rotation. .

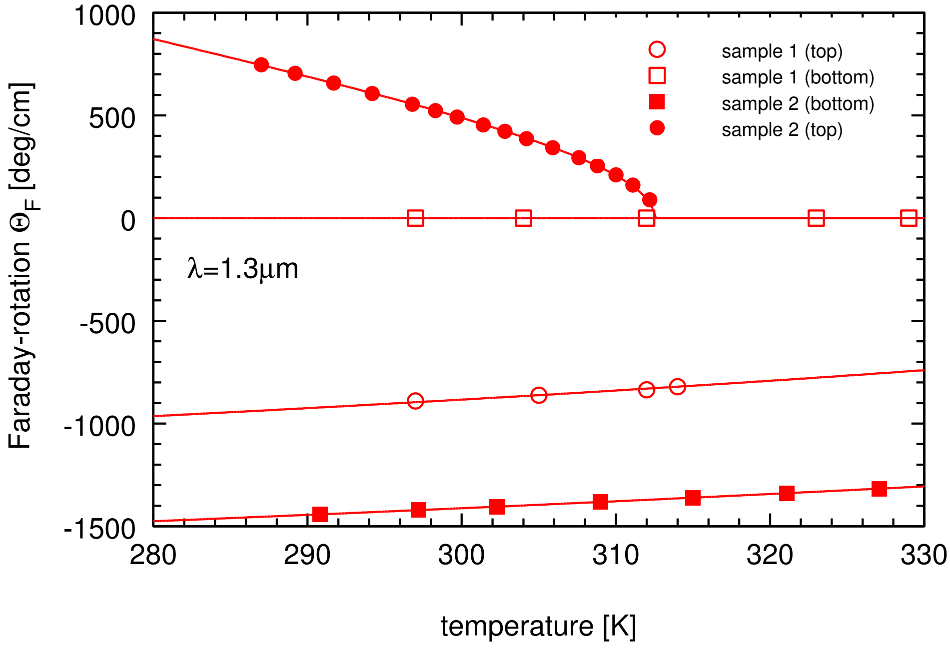


Figure 2: Measured temperature dependence of the Faraday-rotation $\Theta_F$ fitted to molecular field theory [19]. The composition and the material parameters of both samples are given in Table 1.

Table 1: Material parameters of the investigated films ($\lambda = 1.3$ $\mu$m, $T = 295K$).

| sample | composition | $x$ (f.u.) | $y$ (f.u.) | $z$ (f.u.) | $d$ ($\mu$m) | $\Theta_F$ (deg/cm) | $n$ |
|---|---|---|---|---|---|---|---|
| 1 bottom | $Tm_{3-x}Bi_xFe_{5-y}Ga_yO_{12}$ | 0.71 | 1.71 | 0 | 0.20 | 0 | 2.20 |
| 1 top | $Lu_{3-x}Bi_xFe_{5-y-z}Ga_yAl_zO_{12}$ | - | - | - | 0.40 | -900 | 2.27 |
| 2 bottom | $Lu_{3-x}Bi_xFe_{5-y}Ga_yO_{12}$ | 1.08 | 0.45 | 0 | 0.35 | -1450 | 2.33 |
| 2 top | $Lu_{3-x}Bi_xFe_{5-y}Ga_yO_{12}$ | 1.38 | 1.63 | 0 | 0.35 | 350 | 2.27 |

In Fig. 3 three different geometries are presented together with the calculation of $\Delta\beta$ for single and double layer rib waveguides. The parameters are typical for the films investigated in this paper. It turns out that the double layer with the opposite Faraday-rotation show the highest nonreciprocal phase shift. But also in the case of paramagnetic bottom layer the maximum $\Delta\beta$ is 1.4 times larger as compared to the single layer geometry.

## POLARIZATION MEASUREMENT

The nonreciprocal effect of planar waveguides has been measured by Mizumoto et al. [20] using interference technique and by Gerhardt et al. [21] and Wallenhorst et al. [13] using optical mode spectroscopy. For magneto-optic rib waveguides the nonreciprocal phase shift has been determined by Okamura et al. [22] applying an optical polarization technique. Shintaku et al. [23] applied an improved polarization technique which takes the superposition of TM and TE modes with different mode profiles into account.

To determine the waveguide parameters we used another polarization method presented in ref.[18]. This method, in addition, allows to detect depolarizing effects caused by scattering

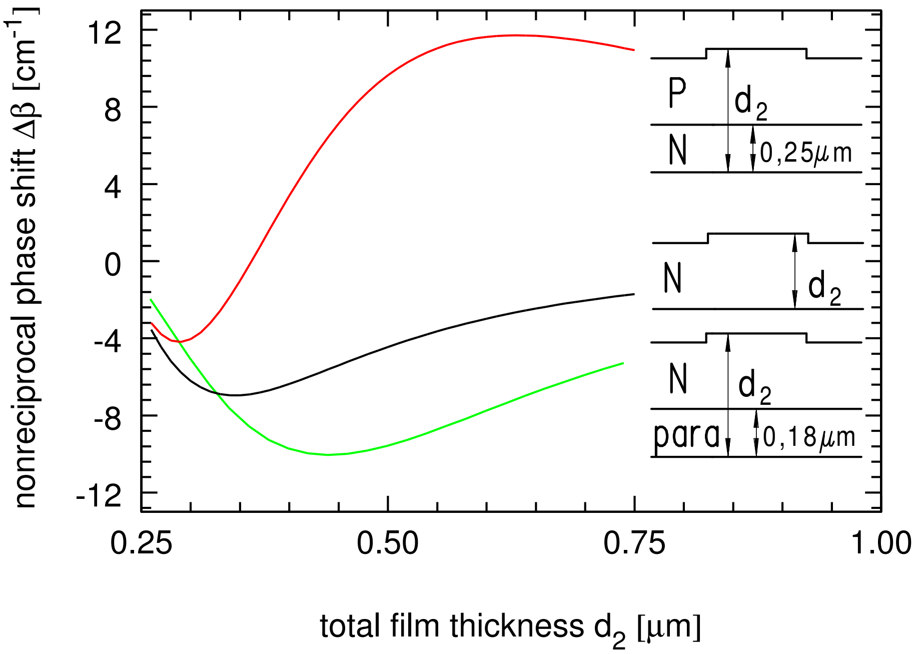


Figure 3: Calculated nonreciprocal phase shift $\Delta\beta$ of the $TM_{00}$-Mode for different waveguide structures at $\lambda = 1.3\ \mu$m. The waveguide parameters of the layer denoted with N are $n = 2.33$ and $\Theta_F = -1450°/\text{cm}$ and for P: $n = 2.27$ and $\Theta_F = +350°/\text{cm}$. The refractive index of the paramagnetic layer is $n$=2.2 . The rib width $w$ and the rib height $h$ are 2.0 $\mu$m and 0.04 $\mu$m and the refractive indices of the substrate and cover are 1.95 and 1, respectively. The thickness of the bottom layer is chosen to yield a maximum for the nonreciprocal phase shift $|\Delta\beta|$.

at defects at the end faces and waveguide flanks and by excitation of higher order modes. Furthermore, we are able to measure the TE/TM modecoupling. For the measurement we couple light of different linear polarizations into the waveguide and determine the polarization of the output light. Then we fit the waveguide parameters to the measured changes of polarization induced by the waveguide. For this purpose we apply the Jones formalism to the modes of the waveguide.

## RESULTS AND DISCUSSION

The calculations displayed in Fig. 3 show that one can enhance $\Delta\beta$ by using double layers. The waveguides with a positive rotating top layer and a negative rotating bottom layer show the highest differential nonreciprocal phase shift [18]. However, the positive rotating film causes a large temperature dependence of $\Delta\beta$. To reduce this effect, the positive rotating film is replaced by a paramagnetic one with negligible Faraday-rotation. In Fig. 4 the temperature dependence of $\Delta\beta$ of two double layer films is displayed. To calculate $\Delta\beta(T)$ of these samples one can use Eq. 5 in the following form:

$$\Delta\beta(T) = \frac{\iint |H_y|^2 k_0/2n(\partial_x \frac{\Theta_i(T)}{\epsilon^2})dxdy}{\iint \epsilon^{-1}|H_y|^2 dxdy} \quad mit \quad i = s, F_1, F_2, c. \tag{6}$$

The functions $\Theta_{F1}(T)$ and $\Theta_{F2}(T)$ are given from measured temperature dependence of

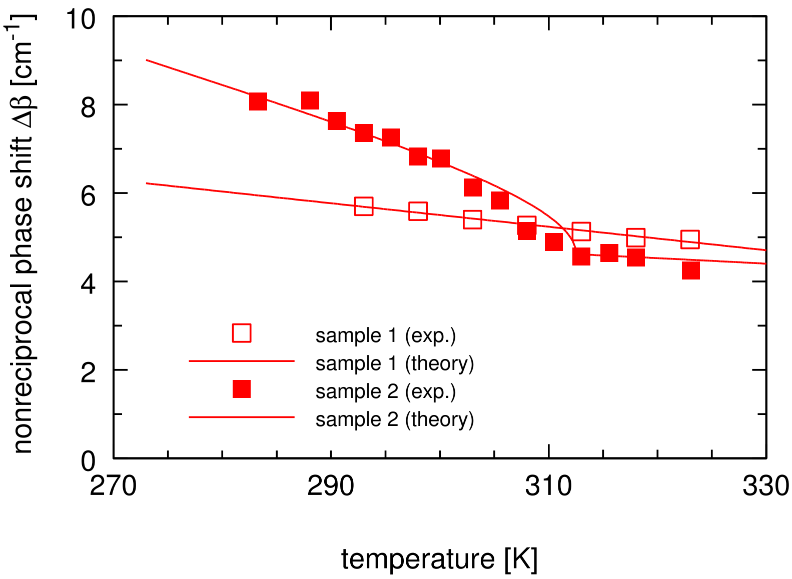


Figure 4: Measured temperature dependence of the nonreciprocal phase shift $\Delta\beta$ as compared with calculations. The composition and the material parameters of both samples are given in Table 1.

Faraday-rotation of the single layers by fitting with a molecular field theory (Fig. 2). The nonreciprocal phase shift $\Delta\beta(T)$ of sample 2 is mainly influenced by the top layer with Curie temperature: $T_C = 313$ K . The small $\Delta\beta$ of sample 1 is caused by the low Faraday-rotation $\Theta_{F2} = -900$ deg/cm. However, the temperature dependence is much better as compared to that of sample 2.

## CONCLUSIONS

Double layer rib waveguides are a good choice to realize nonreciprocal devices. The temperature dependence of the nonreciprocal phase shift $\Delta\beta$ decreases by using double layers with a paramagnetic film instead of a film with positive Faraday-rotation. The further aim is to compensate $\Theta_F(T)$ of the negative rotating top layer by using a positive rotating bottom layer with opposite temperature dependence of $\Theta_F$ in the range between 270 K and 350 K.


## ACKNOWLEDGEMENTS

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