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Investigation of Nonreciprocal Phase Shift Characteristics for Integrated Optical Waveguide Isolators Utilizing Magnetic Photonic Crystals

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1. Introduction

For optical communication systems, the importance of the optical isolators has been increased to protect the devices from a reflected light. However, the currently existing optical isolators are bulky and cannot be integrated with other devices. Thus, the integrated optical isolators are strongly required. Recently, novel devices using magneto-optic effects as the isolators and circulators have been proposed [1,2]. To realize them, the nonreciprocal phase shift depending on the propagation direction of the light is used. The Faraday rotation is the primary factor causing the nonreciprocal phase shift. Therefore, those devices require the materials with large specific Faraday rotation and low optical loss. One-dimensional magnetic photonic crystals are the multi-layers composed of magnetic and dielectric materials. They can deliver the enormous Faraday rotation and Kerr effect in optical wavelength region. Steel *et.al* [3] predicted that the optimization of transmission and large Faraday rotation was possible in two-defect structures by adjusting the separation between the defects. Also, Levy *et.al* [4] showed that the broadband transmission with enhanced Faraday rotation was possible in four defects in magnetic photonic crystals. However all of these works were found out to be the integration-impossible bulky structures.

In this paper, for the first time, we investigated nonreciprocal phase shift characteristics at the wavelength of 1.55μm for optical waveguide isolators with a cladding layer, which is consisted of one-dimensional magnetic photonic crystals to enhance Faraday rotation.

2. Theory

Faraday rotation in one-dimensional Photonic Crystals

The Faraday rotation of one-dimensional magnetic Photonic Crystals (PCs) with two defects are calculated by transfer matrix method [5]. The translation matrix Φ for an example, magnetic photonic crystal is given by

$$\Phi = (\Phi_M \Phi_D)^k (\Phi_D \Phi_M)^m (\Phi_M \Phi_D)^k \tag{1}$$

where translation matrices Φ_M and Φ_D are the magnetic and dielectric layers, respectively. The k and m represent number of layers. The transmission properties are given by comparing the states of incident ($z_{initial}$) and output (z_{final}) light. When the light with the linear polarization is incident of z-direction on one-dimensional magnetic PCs, the output light is given by

$$\begin{bmatrix} C_3 & 0 & 0 & 0 \\ 0 & 0 & C_4 & 0 \\ 0 & 0 & -C_4 & 0 \\ C_3 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \exp(ik(z - z_{final})) \\ \exp(-ik(z - z_{final})) \\ \exp(ik(z - z_{final})) \\ \exp(-ik(z - z_{final})) \end{bmatrix}_{z_{final}} \tag{2}$$

$$= \quad \Phi \begin{bmatrix} 1 & C_1 & 0 & 0 \\ 0 & 0 & 0 & C_2 \\ 0 & 0 & 0 & C_2 \\ 1 & -C_1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \exp(ik(z - z_{initial})) \\ \exp(-ik(z - z_{initial})) \\ \exp(ik(z - z_{initial})) \\ \exp(-ik(z - z_{initial})) \end{bmatrix}_{z_{initial}}$$

where C_i (i=1,2,3,4) are coupling constants. The reflectance ($R=R_x+R_y$), transmission ($T=T_x+T_y$), and Faraday rotation (Θ_F) are obtained by

$$\begin{aligned} & R_x = |C_1|^2, \quad R_y = |C_2|^2 \\ & T_x = |C_3|^2, \quad T_y = |C_4|^2 \\ & \Theta_F = \frac{1}{2}\tan^{-1}\left[\frac{2\,\mathrm{Re}(\chi)}{1-|\chi|^2}\right] \end{aligned} \tag{3}$$

where $\chi = C_4/C_3$.

Nonreciprocal Phase Shift

The magnetic PCs are used as the cladding layers. Also, a semi-conducting layer having its thickness of d is used as a guiding layer. The light propagates to the z direction. When an external magnetic field is applied, the magnetization direction is in-plane of the optical waveguide and transverse to the propagation of the light. In this case, only the nonreciprocal phase shift of the TM mode is occurred. The TM modes of the waveguide is represented by magnetic fields $H=[0,h_y(x),0]\ exp[i(\omega t-\beta z)]$. Assuming that optical loss is neglected, the nonreciprocal phase shift by perturbation theory[6] yields

$$|\Delta\beta| = |\beta_{forward} - \beta_{backward}| = \frac{\int |h_y(x)|^2 \,\partial_x \left(\frac{\xi(x)}{n(x)^4}\right) dx}{\int \frac{1}{n(x)^2} |h_y(x)|^2 dx} \tag{4}$$

where $\beta_{forward}$, $\beta_{backward}$ represent the forward and backward propagation constants, respectively. The *n(x)* denotes the refractive index of each layer of optical waveguide. $\xi(x)$ represents the magneto-optic effect and is given by Faraday rotation Θ_F and the vacuum wave number k_o , $\xi(x) = 2n\Theta_F / k_o$.

Considering the optical waveguide with step index profiles, $\xi(x)$ behaves as a delta function. The nonreciprocal phase shift is calculated as follows:

$$|\Delta\beta| = \frac{\frac{\xi}{n_c}|h_y(d)|^2}{\int \frac{1}{n(x)^2}|h_y(x)|^2 dx} \qquad (5)$$

where n_c is the refractive index of cladding layer.

3. Simulation Results

The multilayer structure is given as $(\Phi_M\Phi_D)^{16}(\Phi_D\Phi_M)^{30}(\Phi_M\Phi_D)^{16}$ for the one-dimensional magnetic PCs. The magnetic and dielectric materials are Ce:YIG(Ce substituted yttrium iron garnet) and GGG(Gallium Gadolium Garnet), respectively [7]. In this structure, the optimized calculation values of Faraday rotation and the length of magnetic PCs are 48.73^o and 23.3μm at the wavelength of 1.55μm. At that time, the thicknesses of GGG and Ce:YIG are 201nm, 175nm, respectively and the transmission of this structure is 81.28%.

Figure 1 represents the calculated nonreciprocal phase shifts for the Ce:YIG/InGaAsP/InP and Ce:YIG/InGaAsP/Air, respectively. The minimum length required for π/2 nonreciprocal phase shift for the Ce:YIG/InGaAsP/Air is nearly 230μm and it is the same result obtained by Yokoi et al [7]. In order to investigate the effects of one-dimensional magnetic PCs structures, we calculate the nonreciprocal phase shifts for the nonreciprocal phase shifter with its length of 230μm and the guiding layer thickness of 0.23μm, which is the optimized guiding layer thickness having maximum nonreciprocal phase shift of Ce:YIG/InGaAsP/Air. The average refractive indices of magnetic PCs used as a cladding layer are calculated with consideration of the GGG and Ce:YIG thickness. Figure 2 shows the nonreciprocal phase shift depending on the number of magnetic PCs as the length of nonreciprocal phase shifter is fixed. The nonreciprocal phase shifts are 1.58, 2.21, 2.85, 3.51 when the number of magnetic PCs are increased from 0 to 3.

4. Conclusions

We designed the multilayer structure consisted of one dimensional magnetic PCs to enhance Faraday rotation. We also calculated the nonreciprocal phase shift of the optical waveguide isolator according to the number of magnetic PCs, which it was used as a cladding layer at the wavelength of 1.55μm. The results show that the presence of magnetic PCs makes more large nonreciprocal phase shift than Ce:YIG is used. It suggests that realization of the innovative integrated optical waveguide isolator is possible.

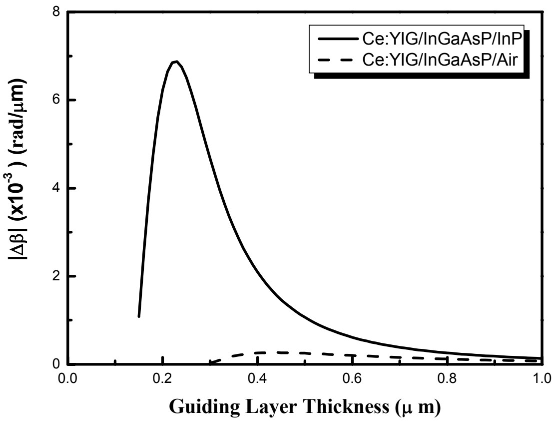

Fig. 1 Calculated nonreciprocal phase shifts for TM$_o$ mode of slab waveguide

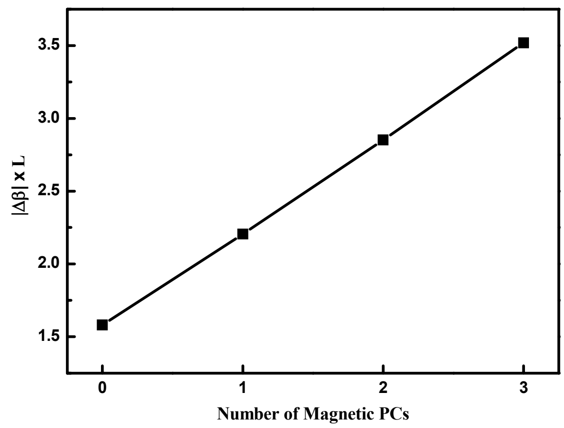

Fig. 2 Calculated nonreciprocal phase shifts depending on number of magnetic PCs (L=230μm).

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