Nonreciprocal Polarization Converter Consisting of Asymmetric Waveguide with Ferrimagnetic Ce:YIG

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***Abstract*—A nonreciprocal polarization converter compatible with InP-based photonic integrated circuits is proposed. The device consists of an asymmetric InGaAsP waveguide combined with a ferrimagnetic Ce:YIG layer. A nonreciprocal TE-TM mode conversion efficiency of 93% can be obtained with a device length of 0.27 mm.**

1 INTRODUCTION

Avoiding the problems caused by undesired reflections of light is a matter of great importance in photonic integrated circuits (PICs). For this purpose, we propose a waveguide-based nonreciprocal polarization converter that can be monolithically combined with other optoelectronic devices on a PIC.

The conventional approach to avoid reflections of light in PICs is creating waveguide-based optical isolators. To date, there are two ways of creating waveguide isolators. One makes use of the nonreciprocal phase shift (NRPS) in a Mach-Zehnder interferometer with a ferrimagnetic garnet layer [1, 2]. The other uses the nonreciprocal propagation loss (NRL) in an optical waveguide combined with an absorbing ferromagnetic metal layer [3, 4]. However, they both are still in the experimental stage and have various problems. The NRPS device needs a large device size (> 2 mm) and a complicated fabrication process, and the NRL device has a large intrinsic loss and therefore needs a high-gain optical amplifier to reduce the insertion loss.

In this paper, we provide a waveguide-based, nonreciprocal polarization converter (NPRC) as a promising means to solve the problem of light reflection. Our polarization converter makes use of the magneto-optical Kerr effect and a phase mode mismatch in an asymmetric waveguide.

2 STRUCTURE OF THE NRPC DEVICE

The function of a NRPC is a nonreciprocal TE-TM mode conversion of light. Incident light of TE mode passing through a NRPC in the forward direction maintains its TE mode and goes out of the output edge. In contrast, backward traveling TE-mode light from the output edge is transformed into a TM mode. Putting a NRPC after a laser diode can remove the instability of the laser caused by backward light because the TE-mode laser is insensitive to TM-polarized light.

To make a NRPC compatible with InP-based PICs, we propose a device shown in Fig. 1. The device consists of an asymmetric InGaAsP waveguide and a ferrimagnetic Ce:YIG layer attached on the top of the waveguide. The YIG layer is magnetized in the direction indicated by the arrow. Fabrication techniques for asymmetric waveguides [5] and wafer bonding techniques to combine garnet crystals with III-V compound semiconductors [1] have been established. Therefore, our device can actually be constructed.

An asymmetric waveguide has two rotated orthogonal modes of polarization (see Fig. 2). An incoming TE-mode wave excites these two modes with different propagation constants β_1 and β_2, which depend on the device structure. Because of the magneto-optic transverse Kerr effect, the propagation constants for forward light are different from those for backward light. Given the appropriate values of the propagation constants, the excited two modes recombine to a TE mode for forward and to a TM mode for backward at a certain distance from the incidence point. The distance is given by

$$L = \frac{2\pi}{\left|\beta_{1f} - \beta_{2f}\right|} = \frac{\pi}{\left|\beta_{1b} - \beta_{2b}\right|}, \quad (1)$$

where β_{1f}, β_{2f} and β_{1b}, β_{2b} are the forward and backward propagation constants of the two orthogonal modes. Our NRPC has two advantages compared with the conventional waveguide isolators. First, the size of the device can be far smaller (< 0.3 mm). Second, the device can be operated without external magnetic fields because the Ce:YIG has a large remanence to operate the device.

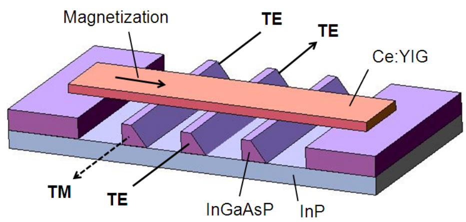

Fig. 1 Nonreciprocal polarization converters consisting of asymmetric InGaAsP waveguides with ferrimagnetic Ce:YIG. Three converters on an InP substrate are shown.

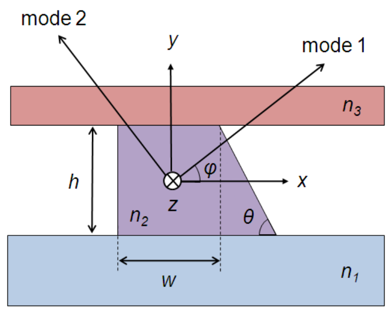

Fig. 2 Cross sectional view of the device.

3 CALCULATING THE DEVICE OPERATION

We confirmed the operation of our device through a simulation using the finite-difference method (FDM). The structure of the device is depicted in Fig. 2. The InGaAsP asymmetric waveguide (n_2 = 3.38, λ_g = 1.25 µm) is sandwiched in between an InP substrate (n_1 = 3.16) and a Ce:YIG layer (n_3 = 2.2). The waveguide has an asymmetric structure with a vertical side-wall and a slanting side-wall oriented along the (111) crystal plane (θ = 53°). In simulation, the wavelength of light was set to 1.55 µm. The thickness *h* of the waveguide was set to 1.1 µm, and the width *w* was changed from 0.9 µm to 1.4 µm.

From Maxwell's equations, we obtained full-vector wave equations including the terms for the magneto-optical effect induced by the Ce:YIG layer. The equations are

$$\partial_x{}^2 E_x + \partial_y{}^2 E_x + (k_0{}^2\varepsilon_r - \beta^2)E_x + \partial_x\left(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x\right) + \partial_x\left(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y\right) + \alpha\omega\mu_0\partial_x\left(\frac{H_x}{\varepsilon_r}\right) = 0 \quad (2)$$

$$\partial_x{}^2 E_y + \partial_y{}^2 E_y + (k_0{}^2\varepsilon_r - \beta^2)E_y + \partial_y\left(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x\right) + \partial_y\left(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y\right) + \alpha\omega\mu_0\partial_y\left(\frac{H_x}{\varepsilon_r}\right) + jk_0{}^2\alpha E_z = 0 \quad (3)$$

where α is the off-diagonal element in the dielectric tensor for the Ce:YIG layer. This element is related to the Faraday rotation coefficient Θ through equation $\alpha = 2n\Theta/k_0$ (Θ in Ce:YIG is -4500 deg/cm at 1.55 µm). In non-magnetic regions (InGaAsP waveguide and InP substrate), α = 0 and Eqs. (2) and (3) are consistent with normal full-vector wave equations.

To solve the wave equations numerically, we partition the domain in space using an 80×80 mesh with a mesh width of 50 nm. From the wave equations, we obtained finite-difference equations by using the discrete form of the differential operators in normal full-vector wave equations (see [6] for these operators). We solved these equations numerically to obtain propagation constants β_1, β_2 for two orthogonal modes and electric field components $E_{x,y}$ in the device. Using these results, we calculated the rotation parameter *R* (see [7] for this parameter) and the half beat length L_π defined by

$$R = \left|\frac{\iint \varepsilon(x,y)E_y(x,y)^2\,dxdy}{\iint \varepsilon(x,y)E_x(x,y)^2\,dxdy}\right|, \qquad L_\pi = \frac{\pi}{|\beta_1 - \beta_2|}, \quad (4)$$

for forward and backward propagations. Figure 3 depicts the values of *R* and L_π as a function of device width *w* (*R* represents the angle of one of the modes; *R* = 1 means φ = 45°).

To achieve an effective nonreciprocal polarization conversion, (I) the rotation parameter *R* should be near 1 to achieve almost complete TE-TM mode conversion, and (II) the half-beat length for backward light must be twice as large as that for forward light (i.e., Eq. (1) must be satisfied). Figure 3 shows that these requirements can be met if the width (at the top) of the waveguide is 1.0 µm.

For the device with this waveguide width, we calculated the power distribution of propagating light along the z–axis by solving the following equation that is obtained from the

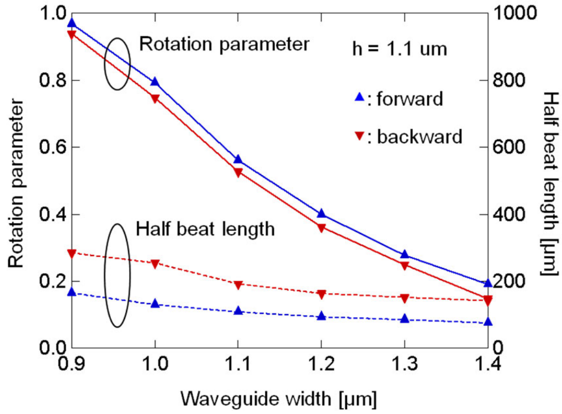

Fig. 3 Rotation parameter and half beat length as a function of the width of the waveguide, calculated for forward and backward propagations.

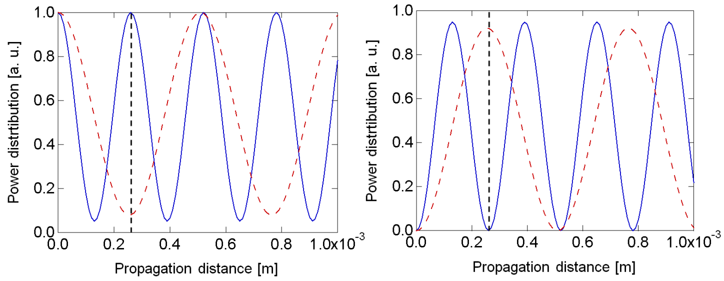

Fig. 4 Power distribution along the z–axis in the device as a function of the propagation distance with a linearly TE-polarized input for forward (solid line) and backward (dashed line) propagating light, calculated for TE-polarized light (left), and TM-polarized light (left).

vectorially corrected (VC) approach (see [8] for this approach). The equation is

$$u(z) = \frac{1 - \exp\left(iz|\beta_1 - \beta_2|\right)}{R + \frac{1}{R}\exp\left(iz|\beta_1 - \beta_2|\right)} \quad (5)$$

where u(z) is the polarization state of an optical signal launched inside the device. To solve Eq. (5), we used the propagation constants β_1, β_2 obtained from the finite-difference equations and the rotation parameter *R*.

Figure 4 shows the calculated power distribution along the z–axis as a function of the propagation distance for a linearly TE-polarized input, for forward (solid line) and backward (dashed line) propagating light. A nonreciprocal polarization conversion of 93% can be obtained with a device length of 0.27 mm. This way, we can develop waveguide-based nonreciprocal polarization converters for PICs.

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