Optical Waveguide Isolator Based on Nonreciprocal Loss/Gain of Amplifier Covered by Ferromagnetic Layer

Wadim Zaets and Koji Ando

***Abstract*—The effect of nonreciprocal loss/gain of a waveguide optical amplifier covered by an absorbing magnetooptic layer was studied for the first time. It is shown that the optical loss/gain of this amplifier differs for the forward and backward propagation when the magnetization is perpendicular to the light propagation and lies in the film plane. Using this effect a new design of an optical isolator is proposed, which is beneficial for monolithic integration of the optical isolator with a laser diode. A calculation predicts an isolation ratio as high as 180 dB/cm for $GaAs_{1-x}P_x$–$Al_{1-x}Ga_xAs$ optical amplifier covered by a Co layer.**

***Index Terms*—Integrated optoelectronics, magnetooptic effects, magnetooptic isolators, optical isolators, semiconductor lasers, semiconductor optical amplifiers.**

I. INTRODUCTION

PROGRESS in optical communication systems requires an ever higher level of integration of different optical elements. The optical isolator is an essential component of such integration. It protects laser diodes and optical amplifiers from unwanted reflections and is necessary to ensure source stability, especially when the fast switching and a large bandwidth are required. Several types of waveguide optical isolators were successfully demonstrated using magnetic garnet films grown on oxide substrates [1]–[4]. Recently, numerous attempts have been made to achieve a monolithical integration of the optical isolator with optical active devices (such as laser diode, optical amplifier, modulator, optical gate) on a semiconductor substrate. A direct bonding of garnet films was proposed onto InP substrate [5] and onto GaAs substrate [6]. Zaets *et al.* [7] experimentally demonstrated that a magnetooptic (MO) film of a diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ grown on GaAs substrate can operate as a waveguide. Hammer *et al.* [8] proposed to use the MO properties of the ferromagnetic metal. They showed theoretically that a nonreciprocal TE–TM mode converter can be obtained using a semiconductor waveguide covered by a Fe layer with a periodical reversal of magnetization. The magnetization direction was considered to be parallel to the light propagation. An optical amplification by the semiconductor waveguide was used to compensate the loss induced by the metal film.

In this letter, we show that an optical semiconductor amplifier covered by a ferromagnetic layer has a large difference in values of loss/gain for modes propagating in the opposite directions when the magnetization is perpendicular to the light propagation direction and lies in the film plane. Thus, the amplifier covered by ferromagnetic can itself act as an optical isolator. This design of the isolator can be beneficial for a monolithic integration of the optical isolator with semiconductor optoelectronic devices.

II. THEORY

In a case of light propagation in a bulk MO material the nonreciprocal effect (variation of optical properties for opposite directions of light propagation) occurs only when the magnetization of the material is parallel to the light propagation (Faraday effect and magnetic circular dichroism). There is no nonreciprocal effect, if the light propagates perpendicularly to the magnetization. Contrary, in the case of MO planar waveguides, if magnetization is perpendicular to the light propagation direction and lies in the film plane, the TM mode has a nonreciprocal change of the propagation constant [9]–[11]. Such effect originates from the nonreciprocal change of the reflectivity at the boundary between two layers, one or both of which are magnetooptic.

To explain this, let us consider a simple MO waveguide (Fig. 1), which consists of isotropic core and cladding layers with the refractive indices $\sqrt{\varepsilon_c}$ and $\sqrt{\varepsilon_3}$, respectively, and a transversally magnetized MO cover layer with the permittivity tensor:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_2 & 0 & -i \cdot \varepsilon_{xz} \\ 0 & \varepsilon_1 & 0 \\ i \cdot \varepsilon_{xz} & 0 & \varepsilon_1 \end{pmatrix}. \tag{1}$$

The complex reflection coefficient for TM-polarized wave at the interface between MO cover layer 1 and isotropic core layer 2 can be written as [12][1]

$$r_{21} = e^{-i \cdot \theta_{21}} \tag{2}$$

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[1] Equations (2) and (3) describe transverse Kerr effect. See, for example, [12].

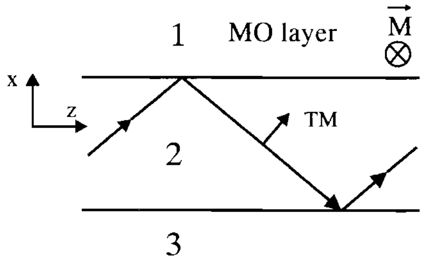

Fig. 1. Zig-zag propagation in a waveguide covered by a magnetooptic layer (1). Core (2) and cladding (3) layers are isotropic.

where

$$\theta_{21} = 2 \cdot \arctan\left(\frac{1}{\frac{\varepsilon_1 k_{x2}}{\varepsilon_2 k_{x1}}\left(1 - \frac{\varepsilon_{xz} \cdot k_z}{\varepsilon_1 \cdot k_{x1}}\right)}\right) \tag{3}$$

and k_z, k_{x1}, k_{x2} are z and x components of the wave vector in the layers.

θ_{21} of (3) depends on the sign of the k_z. Then, the reflectivity [(2)] is different whether the light comes from the right-hand side or from the left-hand side relatively to the magnetization direction ($k_z = +|k_z|$ or $k_z = -|k_z|$).

If all the layers are nonabsorbing (ε_1, ε_2, ε_3, and ε_{xz} are real), the propagation constant k_z of a guided mode is determined by a dispersion relation

$$2 \cdot k_{x2} t = \theta_{21} + \theta_{23} + 2\pi \cdot m \tag{4}$$

where t is a thickness of the core layer 2, θ_{23} is a reciprocal phase shift of the reflection at the boundary between the core layer 2 and the cladding layer 3, and m is a mode number. Equation (4) expresses a condition that the phase shift of a full period of a plane-wave zigzag propagation inside the waveguide should be an integer multiplied by 2π. Because θ_{21} is different for the forward and backward waveguide modes, according to (4) the mode propagation constant also depends on the propagation direction. This property of nonreciprocal phase shift in MO waveguide has been already used to design nonreciprocal devices: an isolator (where the MO waveguide was one of the arms of the Mach–Zehnder interferometer [10]) and a circulator (where the MO waveguide was one of arms of the directional coupler [11]).

Next, let us consider a case that the MO layer is absorbing. Because ε_{xz} and ε_1 become complex, the absolute value of the reflectivity [(2)] becomes smaller than 1, i.e., the light loses some intensity when reflected from the absorbing MO layer. According to (3), the value of this loss depends on the propagation direction. Therefore, the TM modes in the waveguide structure of Fig. 1 have different values of optical loss for the opposite propagation directions.

The mode loss can be reduced or suppressed, if the waveguide core layer provides optical amplification. The internal gain of this layer can be adjusted so that in the forward direction the guided mode is amplified while in the backward direction the mode is absorbed. In this case, such a waveguide acts as an optical isolator for TM polarized light. To suppress propagation of TE-polarized light through the isolator, it is required for the core layer to have a higher internal gain for TM polarization than for the TE polarization. This condition can be satisfied for the tensile-strained amplifying layer [13].

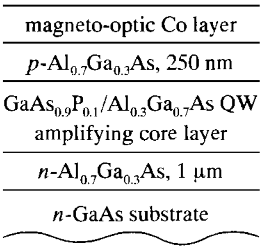

Fig. 2. Schematic diagram of the optical amplifier covered by ferromagnetic metal. The 156-nm-thick amplifying layer includes three 16 nm GaAs$_{0.9}$P$_{0.1}$ tensile-strained QW's with 27-nm Al$_{0.3}$Ga$_{0.7}$As barriers. The absorption by the Co layer is compensated by an optical gain in the amplifying core layer.

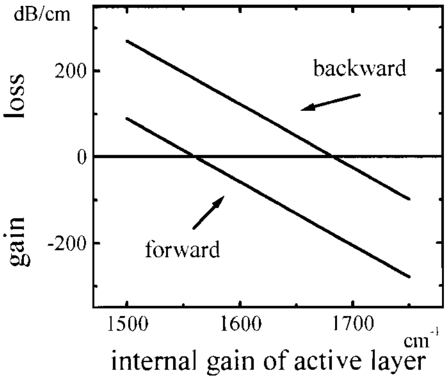

Fig. 3. Waveguide loss/gain as a function of the internal gain of GaAs$_{0.9}$P$_{0.1}$ active layer.

III. Numerical Results

As an example of the waveguide isolator operating at a wavelength of 790 nm, we consider a GaAs$_{0.9}$P$_{0.1}$–Al$_{0.3}$Ga$_{0.7}$As quantum-well (QW) optical amplifier covered by Co layer (Fig. 2). To reduce the absorption by the Co layer, a buffer layer of p-Al$_{0.7}$Ga$_{0.3}$As is inserted between the absorbing Co layer and GaAs$_{0.9}$P$_{0.1}$–Al$_{0.3}$Ga$_{0.7}$As QW amplifying core layer. The optical field of a waveguide mode exponentially penetrates through the buffer layer into the Co layer.

The propagation constants of the waveguide modes were calculated by solving Maxwell equations for the multilayer structure. Refractive indices for Al$_{1-x}$Ga$_x$As, GaAs$_{1-x}$P$_x$ and Co were taken from [14] to [16]. The off-diagonal element ε_{xz} of permittivity tensor [(1)] for Co was calculated from the experimental data of polar Kerr rotation and polar Kerr ellipticity [17], $\varepsilon_{xz} = 0.179 - 1.21i$.

Fig. 3 shows the dependence of the optical loss/gain for the forward and backward propagating modes as a function of internal gain of the GaAs$_{0.9}$P$_{0.1}$ active layer. Depending on the value of the internal gain, the waveguide can operate as a nonreciprocal amplifier (internal gain > 1680 cm^{-1}) or as a nonreciprocal absorber (internal gain < 1560 cm^{-1}) or as an isolator (1560 cm^{-1} > internal gain > 1680 cm^{-1}). The

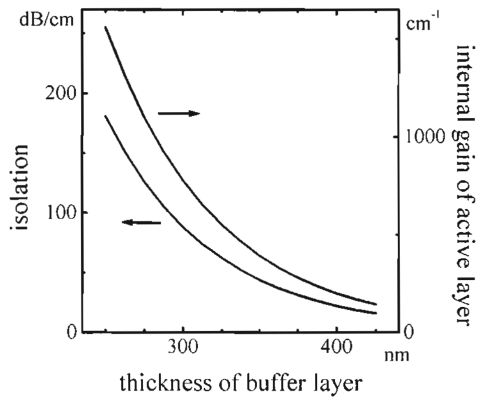

Fig. 4. Isolation ratio and the required internal gain of GaAs$_{0.9}$P$_{0.1}$ active layer versus thickness of p-Al$_{0.7}$Ga$_{0.3}$As buffer layer. The loss/gain of the mode propagating in forward direction is fixed to be zero.

isolation ratio is almost constant against internal gain and it is about 180 dB/cm.

Because the waveguide mode interacts with the MO Co layer by its exponential tale through the buffer layer, the nonreciprocal loss/gain depends on the thickness of the buffer layer. Fig. 4 shows a dependence of the isolation ratio and the internal gain of GaAs$_{0.9}$P$_{0.1}$ active layer as function of the thickness of the p-Al$_{0.7}$Ga$_{0.3}$As buffer layer when the value of loss for the mode propagating in forward direction is kept to be zero. The thinner the buffer layer is, the larger isolation ratio can be obtained, although the higher amplification is necessary to compensate the loss.

The proposed design of the isolator does not require the periodical reverse of magnetization [1], [8] or the phase matching between TE and TM modes [1] or the interferometer structure [1], [10], [11]. It provides the high isolation ratio in a wide range of the internal gain. The isolation ratio is proportional to the isolator length. All of these merits make this design to be suitable for the monolithical integration of optical isolator with optoelectronic devices.

It should be noted that MO materials (ferromagnetic metals, magnetic semiconductors and magnetic garnets) show the highest values of the MO effect in a wavelength region where they show large absorption. Thus, the combination of the absorbing MO materials with the optical amplifiers is a viable way to achieve smaller size of nonreciprocal devices, which is suitable for integrated circuits.

IV. CONCLUSION

We have shown that in a structure of the waveguide amplifier covered by ferromagnetic layer, optical loss/gain is different for the forward and backward light propagation when the magnetization is perpendicular to the light propagation and lies in the film plane. This effect originates from the nonreciprocal features of reflection from the absorbing magnetooptical layer. The effect can be used to make an optical isolator which is suitable to be integrated monolithically with semiconductor optoelectronic devices. For GaAs$_{1-x}$P$_x$–Al$_{1-x}$Ga$_x$As quantum-well optical amplifier covered by Co layer, the isolation ratio of 180 dB/cm can be obtained at a wavelength of 790 nm.

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