TM MODE WAVEGUIDE OPTICAL ISOLATOR BASED ON THE NONRECIPROCAL LOSS SHIFT

Tomohiro Amemiya, Hiromasa Shimizu, and Yoshiaki Nakano

Research Center for Advanced Science and Technology, The University of Tokyo, JST-SORST
4-6-1 Komaba, Meguro-ku, Tokyo, 153-8904, Japan (Email: ametomo@hotaka.t.u-tokyo.ac.jp)

Abstract

We developed a TM mode waveguide optical isolator based on the nonreciprocal loss shift. The isolator consists of a semiconductor optical amplifier with a Ni/Fe ferromagnetic bilayer electrode. An isolation of 6.6 dB/mm was achieved for a wavelength of 1530 nm.

I. Introduction

For further development of optical communication networks, it is important to realize photonic integrated circuits that combine various optoelectronic devices monolithically on a semiconductor substrate. In such photonic integrated circuits, optical isolators are indispensable for avoiding the instable operation of the laser diodes due to undesirable reflection of light from the transmission system. For this purpose, *waveguide optical isolators* [1-5] have great advantage over conventional bulk isolators. They can be monolithically integrated with other waveguide devices such as semiconductor lasers, optical modulators, and switches, which contribute to the reduction of the production cost of photonic integrated circuits.

The phenomenon of the nonreciprocal loss shift is effective for creating the nonreciprocal function in waveguide optical isolators [6-9]. Recently, we fabricated a waveguide optical isolator based on the TE mode nonreciprocal loss shift and demonstrated a 14.7 dB/mm nonreciprocal propagation in an InGaAsP active waveguide with a ferromagnetic Fe layer [10, 11]. For realizing polarization independent waveguide optical isolators, TM mode waveguide optical isolators are also necessary. In this paper, we report a *TM mode* waveguide isolator based on the nonreciprocal loss shift.

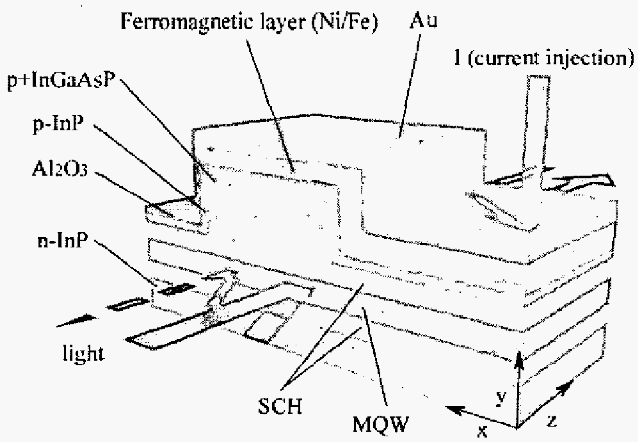

Fig. 1 Structure of the TM-mode waveguide optical isolator based on the nonreciprocal loss shift.

II. The device structure of the TM mode waveguide isolator based on the nonreciprocal loss shift

Fig. 1 shows the device structure of our TM mode waveguide isolator based on the nonreciprocal loss shift. The device consists of a TM mode semiconductor optical amplifier (SOA) covered with a ferromagnetic Ni/Fe bilayer electrode. The ferromagnetic layer is magnetized perpendicular to the light propagation and parallel to the substrate. In this structure, there is a difference in the adsorption coefficient of TM mode between the forward and backward propagation light (see Fig. 2). The injection current *I* for the SOA is adjusted so that the net absorption loss of the forward propagating light is zero (dashed lines in Fig. 2). Under these conditions, the device can act as an optical isolator. Unlike conventional optical isolators,

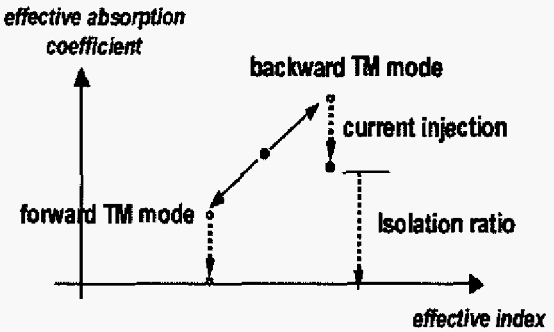

Fig. 2 The principle of the operation of the TM mode optical isolator based on the nonreciprocal loss shift.

0-7803-8891-7/05/$20.00 ©2005 IEEE

polarizers are not necessary for operation. Therefore this isolator can be easily integrated with other optoelectronic devices.

Ⅲ. Simulation of the optical isolator operation

In this optical isolator, TM mode light experiences nonreciprocal loss shift during its travel in the waveguide. The nonreciprocal loss shift comes from the off-diagonal elements in the dielectric tensor of the ferromagnetic layer.

When the magnetization in the ferromagnetic layer is perpendicular to the light propagation (z axis) and parallel to the substrate (x axis), from Maxwell's equations and the boundary conditions for H_x and E_z, we can obtain that

$$(-m_{12}\frac{\beta_1\beta_9}{\varepsilon_1\varepsilon_9}+m_{21})+(m_{11}\frac{\beta_9}{\varepsilon_9}+m_{22}\frac{\beta_1}{\varepsilon_1})j=0 \tag{1}$$

$$\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \left(\prod_{m=2}^{8}\mathbf{M}_m\right)$$

$$\mathbf{M}_m = \begin{pmatrix} \cosh(\beta_m d_m)+\frac{\alpha_m\beta}{\beta_m\varepsilon_m}\sinh(\beta_m d_m) & \frac{\varepsilon_m^2-\alpha_m^2}{j\beta_m\varepsilon_m}\sinh(\beta_m d_m) \\ \frac{j}{\varepsilon_m^2-\alpha_m^2}\left(\beta_m\varepsilon_m-\frac{(\alpha_m\beta)^2}{\beta_m\varepsilon_m}\right)\sinh(\beta_m d_m) & \cosh(\beta_m d_m)-\frac{\alpha_m\beta}{\beta_m\varepsilon_m}\sinh(\beta_m d_m) \end{pmatrix}$$

$$\beta_m=\sqrt{\beta^2-k_0^2\varepsilon_m}$$

where $\varepsilon_m = n_m^2$ (m = 1-9) (n_m is a refractive index) are diagonal elements of the dielectric tensor in the device layers, i.e., n-InP substrate (m = 1), bottom SCH layer (m = 2), MQW active layer (m = 3), upper SCH layer (m = 4), p-InP cladding layer (m = 5), p+ InGaAsP contact layer (m = 6), Ni layer (m = 7), Fe layer (m = 8), and Au electrode (m = 9). β_m, α_m, and d_m are the propagation constant, the off-diagonal element of the dielectric tensor which brings magneto-optical effect, and the thickness of each layer.

Table 1 Parameters for the simulation in our TM mode waveguide optical isolator based on the nonreciprocal loss shift.

Material	m	n_m	α_m	d_m (nm)	PL (nm)
n-InP	1	3.16	0	-	918
bottom SCH	2	3.4	0	100	1100
MQW	3	3.53	0	147	1550
upper SCH	4	3.4	0	100	1100
p-InP	5	3.16	0	150	918
P+InGaAsP	6	3.37	0	150 - 350	1400
Ni	7	3.1+7.71I	0.8-1.05I	5 or 20	-
Fe	8	3.17+5.27I	1.8-3.15I	100	-
Au	9	0.3+13I	0	-	-

Table 1 shows parameters that we used in the simulation. The thickness of the p-InP cladding layer is chosen so that the propagating light can interact the magneto-optical Fe/Ni layer and the p+ InGaAsP contact layer (PL wavelength 1400nm) also works as optical evanescent layer for the 1550 nm light. α_m is related to the Faraday rotation in a magnetic substance. Therefore, α_m are 0 in all materials except for the ferromagnetic materials, Fe and Ni. Because light is attenuated strongly in the n-InP layer and the Au layer, we need not set the value of d_m for these two layers need not be set.

Because of the off-diagonal elements, the Eqs. (1) for TM mode includes a nonzero linear term in the effective propagation constant β. Therefore, the equation has a nonreciprocal solution to β. This produces a difference in adsorption coefficient between forward propagating (z direction) light and backward propagating (-z direction) light. In contrast, for TE mode, there are no linear terms in the propagation coefficient, so TE mode shows reciprocal transmission.

Fig. 3 shows the nonreciprocal loss shift for the 1550 nm TM mode as a function of the thickness of the separation layer (p-InP/p+InGaAsP). This is a result calculated for a device with a ferromagnetic layer consisting of a 5nm or 20nm-thick Ni layer and a 100nm-thick Fe layer. In this simulation, the thickness of the p-InP layer was fixed at 150 nm. The isolation ratio is larger for a 5nm-thick Ni layer than for a 20nm-thick Ni layer. This is because for very thin Ni layer, the device is greatly influenced by the Fe layer having strong magneto-optical effect and small absorption loss. The nonreciprocal loss shift of the device is 2.46 dB/mm for the 400nm-thick separation layer (p-InP/p^+InGaAsP layer) and the 20nm-thick Ni layer.

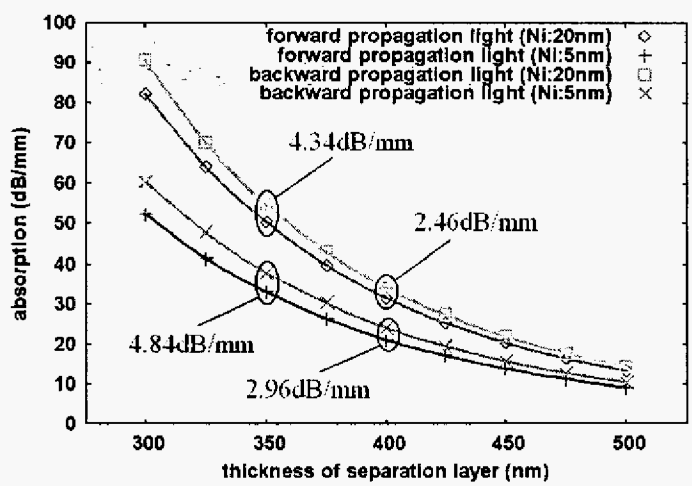

Fig. 3 The calculated absorption loss by a Ni/Fe bilayer (Ni: 5 nm or 20 nm, Fe: 100 nm) for TM mode as a function of the separation layer (p-InP/p+InGaAsP) thickness. In this simulation, the thickness of the p-InP layer was fixed at 150 nm.

IV. Fabrication of the prototype devices

We fabricated the TM mode SOA layer structure on an *n*-InP substrate by metal-organic vapor phase epitaxy (MOVPE). The MQW region consists of five InGaAs wells (15nm-thick, 0.8% tensile-strained) and six InGaAlAs barriers (12nm-thick, 0.6% compressive-strained), with InGaAlAs separate confinement layers for TM mode amplification. The PL wavelength of the MQW layer is 1530nm. We fabricated the device with a separation layer consisting of a 150nm-thick p-InP layer and a 250nm-thick p^+InGaAsP layer, and a ferromagnetic bilayer consisting of a 20nm-thick Ni layer and a 100nm-thick Fe layer. In this device, the Ni layer not only acts as a magneto-optic layer, but also electrically connects the p^+InGaAsP layer and the Fe layer (the main part of the ferromagnetic layer with a strong magneto-optic effect).

Fig. 4 shows the cross-sectional scanning electron microscopy (SEM) image of the fabricated device. The fabrication of the device was as follows. First, the ridge waveguide was formed by a wet etching using a $Br_2/HBr/H_2O$ solution. The width and the depth of the waveguide were set to 5.5 μm and 400 nm. Then, 100nm-thick Al_2O_3 layer was deposited by a electron-beam (EB) evaporation. After that, an Al_2O_3 layer on the top of the p^+InGaAsP contact layer was removed by a lift-off process. Finally, the Ni and Fe layers were deposited with the EB evaporator, and their thicknesses were about 20 nm and 100 nm as mentioned above. In this way, we successfully fabricated the simulated device structure.

Fig. 5 shows an experimental setup for measuring the nonreciprocal loss shift of the device. Input light from a tunable laser with an erbium-doped fiber amplifier (EDFA) was introduced to the device. We measured the propagation characteristics of the device by an optical spectrum analyzer (OSA). An external magnetic filed of 1kG was applied to the device by a permanent magnet. In this experiment, we changed the direction (polarity) of the magnetic field instead of changing the direction of the light propagation.

Fig. 6 shows the propagation characteristics for (a) TM and (b) TE mode. The device was 0.75-mm long, as cleaved, and kept at 17°C by a temperature controller. The bias current was set to 100 mA. The incident light is of 1530 nm wavelength and 8 dBm intensity. For TM mode, the transmission intensity changed by 5.0 dB under a revise of the magnetic field direction. Therefore, the nonreciprocal loss shift in this device was 6.6 dB/mm. In contrast, for TE mode, the transmission intensity was little or no change under a reversal of the magnetic field. Since our device operates only in TM mode, this polarization dependence is a clear evidence of the nonreciprocal propagation.

In this experiment, the compensation of the loss of the forward propagating light by the gain of the SOA is not sufficient. Therefore the absorption loss for the forward propagating light was large. We are now developing an improved device for smaller insertion loss.

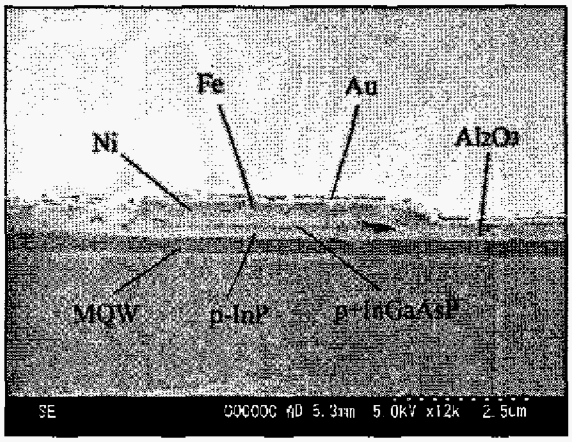

Fig. 4 Cross sectional SEM image of the fabricated TM mode waveguide optical isolator.

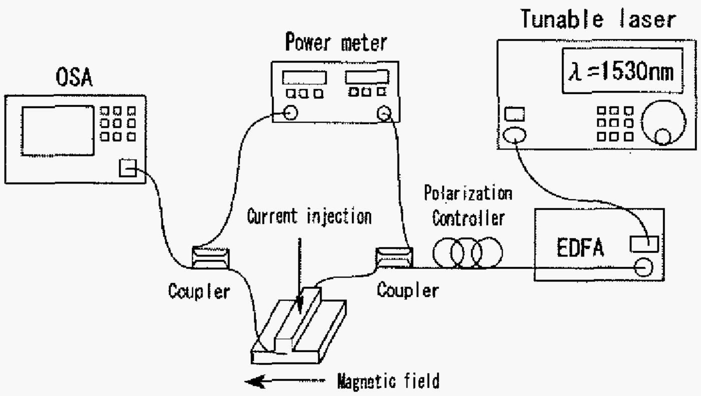

Fig. 5 Experimental setup for measuring the nonreciprocal loss shift

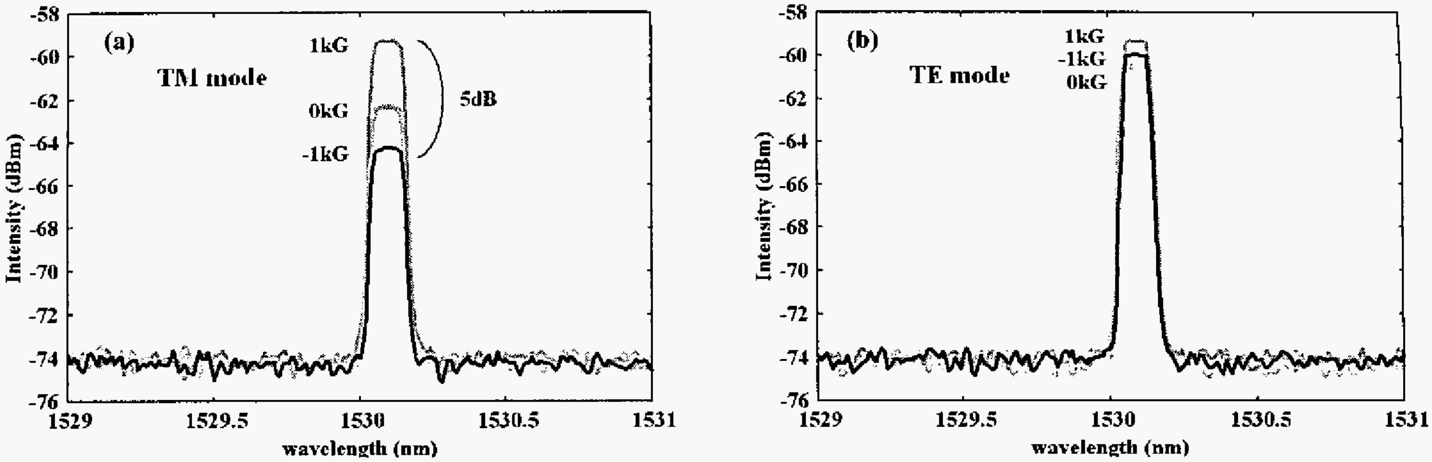

Fig. 6 Propagation characteristics of the device for (a) TM and (b) TE mode, with magnetic fields 1 kG , 0 kG, and -1 kG. A nonreciprocal loss shift was observed only for TM mode.

V. Conclusion

We demonstrated a TM mode waveguide optical isolator based on the nonreciprocal loss shift. The simulation showed a nonreciprocal loss shift of 2.46 dB/mm for the 400nm-thick separation layer (p-InP/p$^+$InGaAsP layer) and the 20nm-thick Ni layer at a wavelength of 1550 nm. Based on these simulations, we fabricated and characterized a prototype device for verifying the principle. In the fabricated InGaAs/InGaAlAs MQW active waveguide optical isolator, 6.6 dB/mm nonreciprocal loss shift was achieved for 1530 nm TM mode light. This is a promising result for the semiconductor optical isolators that can be monolithically integrated with other waveguide devices such as semiconductor lasers, modulators, and switches.

References

[1] K. Ando, *et al., J. Appl. Phys.* **57**, 1277 (1985)

[2] H. Dammann, *et al., Appl. Phys. Lett.* **49**, 1755 (1986)

[3] N. Sugimoto, *et al, J. Lightwave Technology* **14**, No.11, 2537 (1996)

[4] H. Yokoi, *et al., Appl. Optics*, **38**, No. 36, 7409 (1999)

[5] H. Yokoi, *et al., Appl. Optics*, **42**, No. 33, 6605 (2003)

[6] M. Takenaka and Y. Nakano, *Proceeding of 11th International Conference on Indium Phosphide and related materia*ls, 289 (1999).

[7] W. Zaets, and K. Ando, IEEE., *Photon. Tech. Lett.* **11**, 1012 (1999).

[8] M. Vanwolleghem, *et al., Proceedings Symposium IEEE/LEOS* (2002)

[9] M. Vanwolleghem, *et al., Appl. Phys. Lett.* **85**, 3980 (2004)

[10] H. Shimizu and Y. Nakano, *Jpn. J. Appl. Phys.* **43**, L1561 (2004)

[11] H. Shimizu and Y. Nakano, *Optical Fiber Communication Conference,* PDP18 (2005)