TM MODE WAVEGUIDE ISOLATOR MONOLITHICALLY INTEGRATED WITH InP ACTIVE DEVICES

*Gengo Takahashi[1], Tomohiro Amemiya[2], Takuo Tanemura[1], Akio Higo[1], Koji Takeda[1], Yoshiaki Nakano[1]
1: Research Center for Advanced Science and Technology, the University of Tokyo, Japan
2: Quantum Nanoelectronics Research Center Tokyo Institute of Technology, Japan
*gengo@hotaka.t.u-tokyo.ac.jp

Abstract— We propose and experimentally demonstrate a novel structure for monolithically integrating a TM-mode waveguide optical isolator with active InP devices. A semiconductor ring laser with integrated isolator is fabricated and demonstrated for the first time.

I. INTRODUCTION

Optical isolators are indispensable devices for stable operation of telecommunication semiconductor laser diodes (LDs). In particular, monolithically integrated InP waveguide isolators are important in suppressing instability in large-scale photonic integrated circuits (PICs), which includes numerous active devices, such as LDs and semiconductor optical amplifiers (SOAs). For this purpose, various types of waveguide optical isolators have been researched up to date [1-3]. Recently, we have succeeded in demonstrating the first monolithic integration of TE mode waveguide optical isolator with a distributed feedback LD (DFB-LD) [4].

In this paper, we propose and experimentally demonstrate a novel simple method of integrating TM mode isolator [5] on PIC. As a proof-of-concept device, a TM mode semiconductor ring laser (SRL) with monolithically integrated isolator is fabricated using the proposed method for the first time

II. STRUCTURE OF INTEGRATED ISOLATOR

Figure 1 shows the proposed device structure with integrated TM mode isolator and SOA sections. The TM-mode waveguide isolator is realized by using non-reciprocal loss mechanism. It consists of a ferromagnetic Fe/Ni layer in the upper cladding. When the ferromagnetic layer is magnetized perpendicular to the light propagation and parallel to the substrate, the propagation modes split vertically. As a result, backward-propagating light experiences larger loss compared with the forward-propagating light, thus nonreciprocal loss is induced (Fig.1). Under these conditions, the device can act as an optical isolator. The background loss is compensated for by injecting current to the active MQW layer.

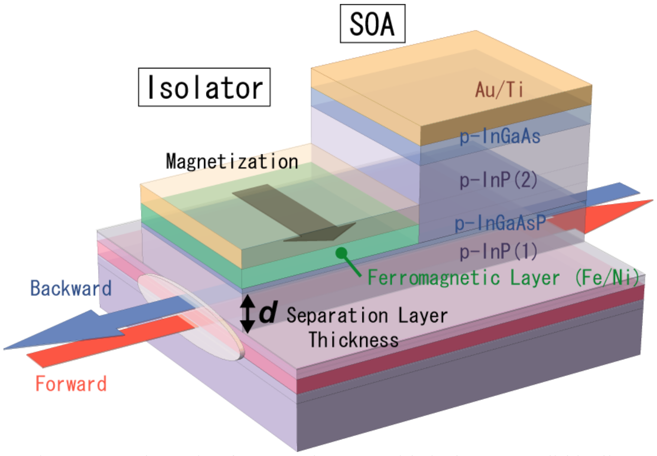


Fig. 1 Schematic of TM-mode waveguide isolator monolithically integrated with SOA. The polyimide is hidden in this figure.

One important requirement to achieve sufficient nonreciprocal loss is that the separation distance between the core and Fe/Ni (*d* in Fig. 1) must be thin (<500 nm), which is typically smaller than thickness of p-clad layer in conventional LDs. Consequently, integration of isolator with conventional SOA requires 2 levels p-clad thickness layers in a substrate. On the other hand, there is a concern of undesirable light reflection and scattering at the interface of such 2 level structure. We then optimize the separation layer thickness with simulations below. Additionaly, to fabricate this 2 level structure with easy way, we propose to embed a p-InGaAsP contact layer in the middle of p-InP layer (Fig.1).

III. SIMULATIONS FOR DESIGN OF INTEGRATED ISOLATOR

A. Nonreciprocal Loss Calculation

A large isolation ratio can be obtained at small cladding-layer thickness because a thin cladding layer easily lets light through into the ferromagnetic layer to produce a large magneto-optic interaction. Therefore, the cladding layer has to be thin as long as the amplifying gain of the SOA can compensate for the absorption loss of light in the ferromagnetic layer.

Figure 2 shows the calculated optical losses for the 1550nm TM mode as a function of p-InP(1) thickness *d*. The nonreciprocal loss (isolation ratio) is difference between the optical absorption loss of forward propagation and the one of backward propagation. This simulation is based on the scalar wave equation including off-diagonal elements in the dielectric tensor of the ferromagnetic layer and calculated with 2D-FDM [6]. As shown in Fig. 2, the nonreciprocal loss reduces as the

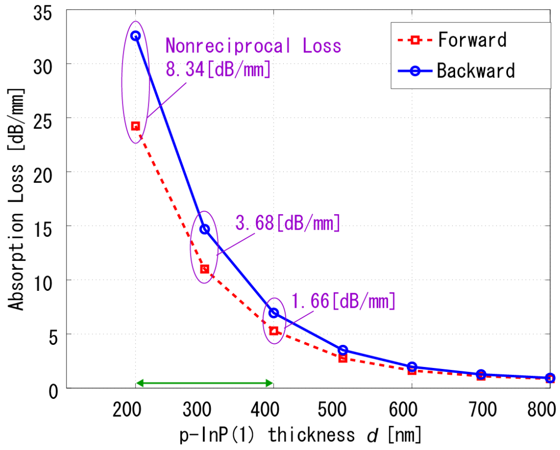


Fig.2 The simulated optical absorption loss for TM mode 1550nm of the isolator as a function of the thickness of p-InP(1) thickness *d*. In this simulation, the thickness of Ni and Fe is fixed to 20nm and 200nm, respectively.

separation *d* increases because the interaction of ferromagnetic layer and light emission is small when *d* is large. On the other hand, when *d* is smaller than 200 nm, the optical loss at the isolator is too large. From this result, *d* should to be 200 ~ 400nm to obtain sufficient nonreciprocal loss.

B. *Estimation the Reflection and Scattering*

As shown in Fig. 1, this device has the 2 level p-cladding and undesirable light reflection and scattering may occur in such structure interface. For estimate the reflection at the interface between SOA and isolator, we calculate the equivalent refractive indexes at SOA and isolator. They are almost same and then the reflection is ignorable. For estimate the scattering, we calculate the overlap integration of the mode distribution on the device cross section at the isolator and SOA. In this simulation, the thickness of the p-cladding of SOA is fixed at 1450nm. The coupling efficiency η can be written as

$$\eta = \frac{\left|\int\int \phi_{SOA}(x,y)\phi_{ISO}(x,y)dxdy\right|^2}{\int\int\left|\phi_{SOA}(x,y)\right|dxdy\cdot\int\int\left|\phi_{SOA}(x,y)\right|dxdy} \quad \cdots\cdots (3.1)$$

Figure 3 shows the calculated coupling ratio between SOA and isolator section as a function of separation *d*. As shown in Fig. 3, the coupling efficiency converges to 100% as the separation *d* increases because isolator p-cladding profile becomes same as SOA. On the other hand, when *d* is smaller than 300 nm, the coupling efficiency is small.

We thus choose *d* to 400nm in the following device fabrication to obtain sufficient nonreciprocal loss and high coupling ratio. The ferromagnetic layer (Ni/Fe) thickness is 20nm and 200nm which is used in previous paper [7].

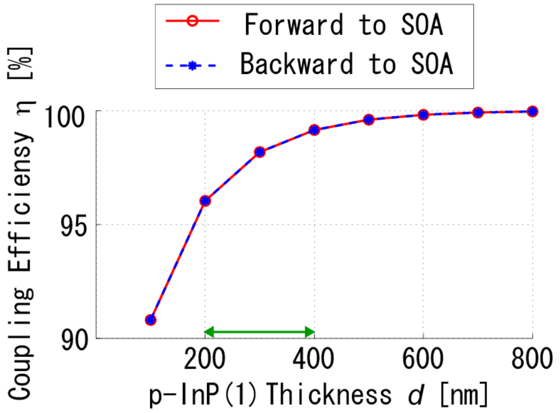


Fig.3 The calcurated mode coupling efficiency between isolator and SOA as a function of the thickness of the p-InP(1); *d*.

Table 1 The epitaxial layer structure in our TM mode SOA integrated with waveguide optical isolator.

Material	**m**	**d_m (nm)**
n-InP	1	-
bottom SCH	2	80
MQW	3	147
upper SCH	4	80
u-InP	5	30
u-InGaAsP	6	5
p-InP(1)	7	400
p+InGaAsP	8	50
p-InP(2)	9	800
p+InGaAs	10	200

The epitaxial structure was similar to that in [5], except that a 50-nm-thick p-InGAsP contact layer was embedded in the middle of p-InP upper cladding. d_m is a thickness of each layer. The all parameters that we used in the simulation are same as [7].

IV. FABRICATION OF SOA WITH INTEGRATED ISOLATOR

To fabricate the 2 level p-cladding structure with easy way, we proposed to embed a p-InGaAsP contact layer in the middle of p-InP layer. p-InP was divided to p-InP(1) and p-InP(2) (Table 1). After the reactive ion etching (RIE) for waveguide ridge structure, p-InGaAs and p-InP(2) only at the isolator section were etched. This process doesn't require re-growth step.

We fabricated the TM mode SOA layer structure which includes isolator structure on an n-InP substrate by metal-organic vapor phase epitaxy (MOVPE). The fabrication of the device was as follows. First, as shown in Fig. 4(1), the ridge waveguide was formed by a standard photolithography and Cl_2/Ar reactive ion etching with SiO_2 mask. As shown in Fig. 4(2), SOA ridge structure was covered with photo resist to prevent followed wet etching. As shown in Fig. 4(3), p+InGaAs and p-InP(2) only at the isolator section were etched with $H_2SO_4/H_2O_2/H_2O$ and HCl, respectively. The layer thickness difference can be created by this additional wet etching. Since it does not require re-growth step, the proposed structure is relatively easy to fabricate without sacrificing the SOA performance. After that, a polyimide was spin coated and ashed to the height of SOA thickness and polyimide at only the isolator section was partly ashed to the height of isolator with SiO2 mask which pattern is same as Fig. 4(2). Polyimide was employed for passivation. As shown in Fig. 4(4), ferromagnetic Ni and Fe layers were deposited only in the isolator section with the electron-beam (EB) evaporator and their thickness were about 20nm and 200nm as mentioned above. Finally, a 100nm Ti layer and a 200nm Au layer were deposited to make a top electrode.

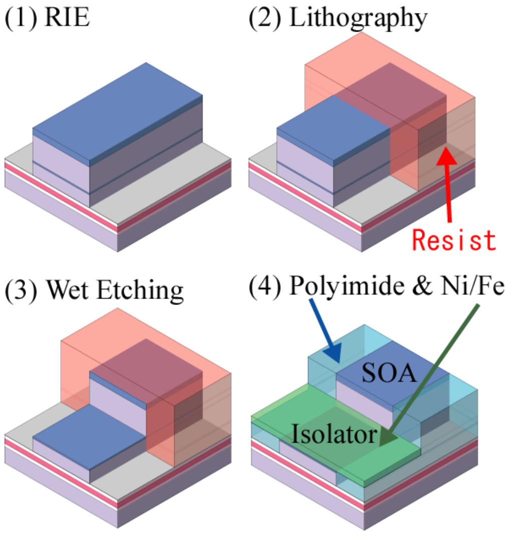


Fig.4 Fabrication images for creating 2 level p-cladding structure

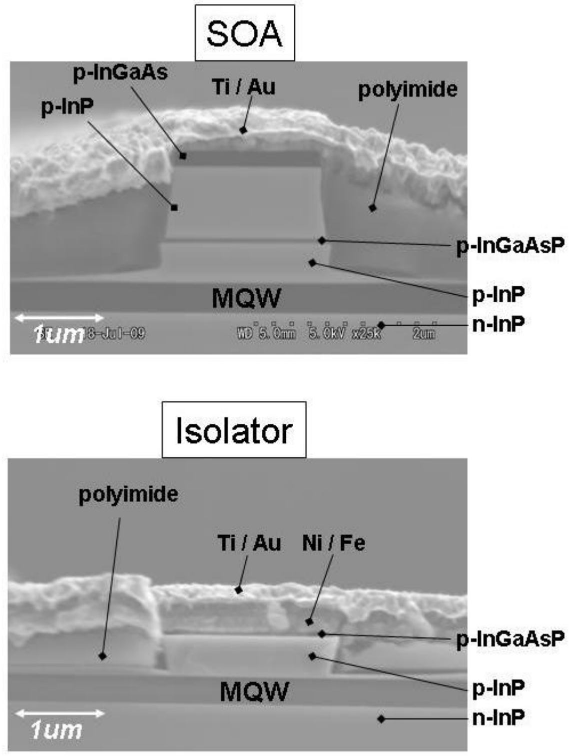


Fig.5 Cross sectional SEM image of the fabricated integrated device, SOA section and isorator section

Figure 5 shows the scanning electron microscope (SEM) image at the intersection of both the SOA and isolator sections.

V. FABRICATION OF RING LASER WITH ISOLATOR

As a proof-of-concept device, a TM-mode SRL with monolithically integrated isolator is fabricated using the fabrication method proposed above.

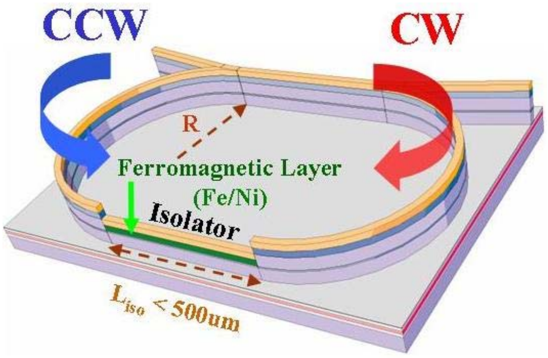


Fig.6 Schematic of TM-mode waveguide isolator monolithically integrated with SRL. Polyimide is hidden in this figure.

SRL has a bistablity of the light oscillation direction. Integrated isolator brings the two different absorption loss (CW (forward) loss < CCW (backward) loss) and suppress CCW oscillation, resulting in unidirectional operation. The loss magnitude relation is defined with the external magnetic field direction and the we can control the SRL oscillation direction with the magnetic field.

We prepare the device design below, ring radius is 300um and 500um, isolator length is 500um and Y-branch optical output and feedback to the cavity ratio is 50%:50%. Figure 7 shows an experimental setup for measuring the IL characteristics and spectrum. An external magnetic field of

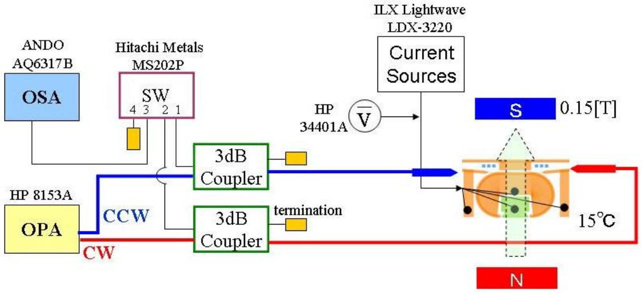
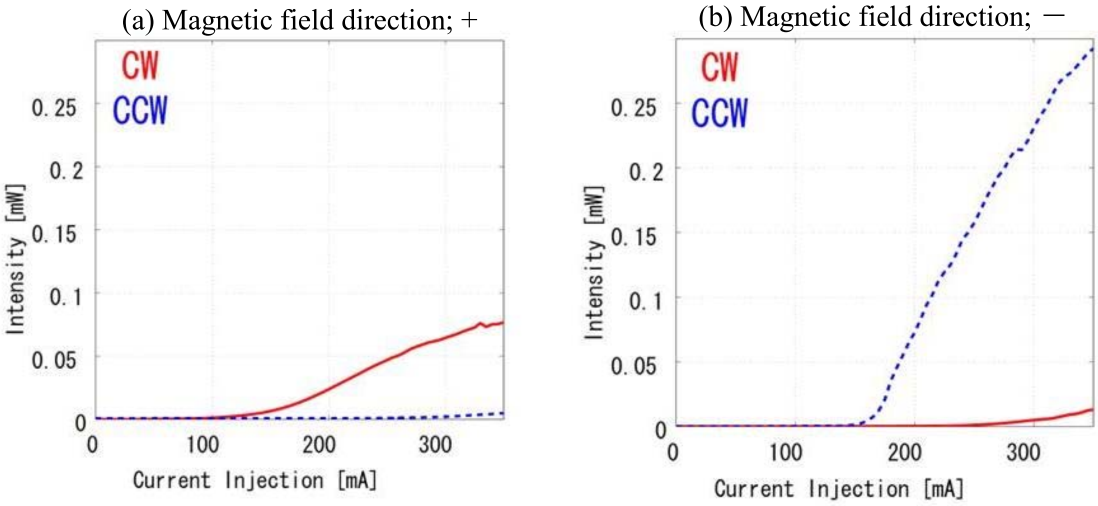


Fig. 7 Experimental setup for measuring the SRL integrated with waveguide optical isolator


(a) Magnetic field direction; +

(b) Magnetic field direction; －

Fig. 8 IL characteristics of the integrated device with magnetic fields +0.15T and -0.15 T.

0.15T was applied to the device by a permanent magnet. In this experiment, we changed the direction (polarity) of the magnetic field. Figure 8 shows the IL characteristics of the fabricated SOA with integrated isolator output from clockwise (CW) and counter-clockwise (CCW) directions. A magnetic fields of ±0.15T is applied laterally during the measurement. The oscillation direction has a dependency of the external magnetic field direction and we observe that only one mode oscillation, corresponding to the smaller-loss direction in the waveguide isolator.

VI. CONCLUSION

We have proposed and demonstrated a simple structure to integrate TM-mode waveguide optical isolator with other InP active devices. By inserting a thin p-InGaAsP contact layer in the middle of p-InP upper cladding, the isolator section was integrated in a relatively simple fabrication process. As a proof-of-concept device, we have succeeded in fabricating a semiconductor ring laser with integrated isolator and demonstrated a preliminary unidirectional lasing characteristic for the first time. The proposed structure can be an effective method to control the direction of lasing mode in a micro-ring laser diode with external magnetic field direction.

REFERENCES

[1] W. V. Parys, B. Moeyersoon, D. V. Thourhout, R. Baets, M. Vanwolleghem, B. Dagens, J. Decobert, O. L. Gouezigou, D. Make, R. Vanheertum, and L. Lagae. “Transverse magnetic mode nonreciprocal propagation in an amplifying algainas/InP optical waveguide isolator,” *Appl. Phys. Lett.*, vol. 88, No. 7, p. 071115, 2006.

[2] J. S. Yang, J. W. Roh, S. H. Ok, D. H. Woo, Y. T. Byun, W. Y. Lee, T. Mizumoto, and S. Lee. “An integrated optical waveguide isolator based on multimode interference by wafer direct bonding,” *IEEE Trans. Magn.*, vol. 41, No. 10, p. 3520, 2005.

[3] V. Zayets, M. C. Debnath, and K. Ando. “Complete magneto-optical waveguide mode conversion in Cd$_{1-x}$Mn$_x$Te waveguide on GaAs substrate,” *Appl. Phys. Lett.*, vol: 84, p. 565, 2004

[4] H. Shimizu and Y. Nakano. “Monolithic integration of a waveguide optical isolator with a distributed feedback laser diode in the 1.5-um wavelength range,” *IEEE Photon. Technol. Lett.,* vol. 19, No. 24, p. 1973, 2007.

[5] T. Amemiya, H. Shimizu, P. N. Hai, M. Tanaka, and Y. Nakano. “Nonreciprocal propagation of light without external magnetic fields in a semiconductor waveguide isolator with a MnAs layer,” *J. Magn. Magn. Mater.*, vol. 310, No. 2, Part 3, p. 2161, 2007.

[6] T. Amemiya, H. Shimizu, M. Yokoyama, P. N. Hai, M. Tanaka, and Y. Nakano. 1.54-μm tm-mode waveguide optical isolator based on the nonreciprocal-loss phenomenon: device design to reduce insertion loss. *Appl.Opt.*, vol. 46, No. 23, p. 5784, 2007.

[7] T. Amemiya, H. Shimizu, and Y. Nakano. TM mode waveguide optical isolator based on the nonreciprocal loss shift. *Conference on Indium Pohsphide and Related Materials*, p. 303, 2005.