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Monolithic Integration of Semiconductor Waveguide Optical Isolators with Distributed Feedback Laser Diodes

Hiromasa SHIMIZU
Tokyo University of Agriculture and Technology
Japan

1. Introduction

Monolithically InP-based photonic integrated circuits, where more than two semiconductor optoelectronic devices are integrated in a single InP substrate, have long history of research and development. Representatives of these InP-based photonic integrated circuits are, electroabsorption modulator integrated distributed feedback laser diodes (DFB LDs) (Kawamura et al., 1987, H. Soda et al., 1990) and arrayed waveguide grating (AWG) integrated optical transmitters and receivers (Staring et al., 1996, Amersfoort et al., 1994). Recently, dense wavelength division multiplexing (DWDM) optical transmitters and receivers have been reported with large-scale photonic integrated circuits having more than 50 components in a single chip (Nagarajan et al., 2005).

However optical isolators have been one of the most highly desired components in photonic integrated circuits in spite of their important roles to prevent the backward reflected light and ensure the stable operation of LDs. Although commercially available "free space" optical isolators are small in size and high optical isolation (>50dB) with low insertion loss (<0.1dB) is already realized, they are composed of Faraday rotators and linear polarizers, which are not compatible with InP based semiconductor LDs. Especially, Faraday rotators are based on magneto-optic materials such as rare earth iron garnets, and they are quite incompatible with InP based materials. Monolithically integrable semiconductor waveguide optical isolators are awaited for reducing overall system size and the number of the assembly procedure of the optical components. Also, such nonreciprocal semiconductor waveguide devices could enable flexible design and robust operation of photonic integrated circuits.

To overcome these challenges, we have demonstrated monolithically integrable transverse electric (TE) and transverse magnetic (TM) mode semiconductor active waveguide optical isolators based on the nonreciprocal loss (Shimizu & Nakano, 2004, Amemiya et al., 2006), and reported 14.7dB/mm optical isolation at λ=1550nm (Shimizu & Nakano, 2006). In this chapter, we report monolithic integration of a semiconductor active waveguide optical isolator with distributed feedback laser diode (DFB LDs).

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2. Fabrication of the integrated devices

The semiconductor active waveguide optical isolators in the integrated devices are based on the nonreciprocal loss. In our TE mode semiconductor active waveguide optical isolators, ferromagnetic metal (Fe) at one of the waveguide sidewalls provides the TE mode nonreciprocal loss, that is, larger propagation loss for backward traveling light than forward traveling light. The gain of the semiconductor optical amplifier (SOA) compensates the forward propagation loss by the ferromagnetic metal (Shimizu & Nakano, 2004 & 2006). Fig. 1 shows the cross sectional image of the TE mode semiconductor active waveguide optical isolator taken by a scanning electron microscope. Since our waveguide optical isolators are not based on Faraday rotation, polarizers are not necessary for optical isolator operation. This is great advantage for monolithic integration of waveguide optical isolators with DFB LDs. The principle of the semiconductor active waveguide optical isolators is schematically shown in Fig. 2 (Takenaka & Nakano, 1999, Zaets & Ando, 1999). Discrete TE mode semiconductor active waveguide optical isolators have been reported in previous papers [Shimizu & Nakano, 2004 & 2006]. In TE mode semiconductor active waveguide optical isolators of Fig. 1, the waveguide width (w) determines the optical isolation and propagation loss characteristics. In narrow waveguides (w = 1.6μm), the optical confinement factor in the Fe thin film at one of the waveguide sidewalls is 0.16%, and the optical confinement factor of 0.16% brings the optical isolation of 14.7dB/mm (Shimizu & Nakano, 2006). Here, the optical isolation and propagation loss are almost proportional to the optical

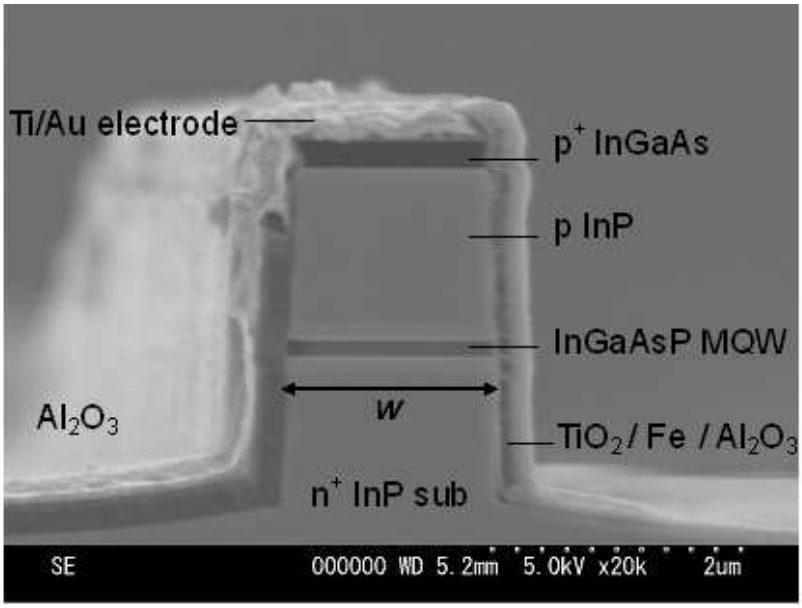

Fig. 1. A cross sectional scanning electron microscope image of a TE mode semiconductor active waveguide optical isolator having Fe layer at one of the waveguide sidewalls. w denotes the waveguide stripe width.

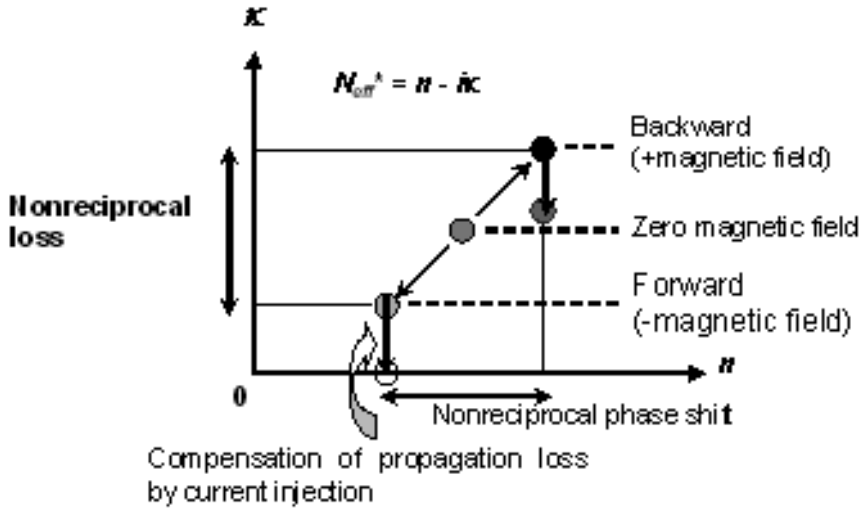

Fig. 2. Schematic operation principle of the semiconductor active waveguide optical isolators based on the nonreciprocal loss.

confinement factor in the Fe layer. As a result, the narrow waveguides work as optical isolators. On the other hand, in wide waveguides (w = 3μm), the optical confinement factor in the Fe thin film at one of the waveguide sidewalls is 0.02%, the propagating light receives small magneto-optic effect and absorption loss from the Fe layer. Hence, the wide waveguides work as LD. Higher optical transverse modes are absorbed by the Fe layer. Fig. 3 shows light output – current characteristics of TE mode semiconductor active waveguide optical isolators with the waveguide width w of 1.7 – 4.5 μm. TE mode semiconductor active waveguide optical isolators of w > 2.2 μm show lasing. On the other hand, TE mode semiconductor active waveguide optical isolators of w < 2.1 μm do not show lasing. This is because the Fe layer at the sidewall provides propagation loss, and non-radiative surface recombination at the etched sidewall reduces the internal quantum efficiency and gain of the MQW active layer. The reduced internal quantum efficiency is one of the problems of TE mode semiconductor active waveguide optical isolators. Thus, we have fabricated the monolithically integrated devices of DFB LDs and semiconductor active waveguide optical isolators in a simple fabrication process (Shimizu & Nakano, 2006).

The monolithically integrated devices are composed of 0.25mm-long index-coupled DFB LD and 0.75mm-long TE mode semiconductor active waveguide optical isolator sections on single InP chip. The DFB LD/semiconductor active waveguide optical isolator layer structures were grown by two steps of metal-organic vapor phase epitaxy (MOVPE) process. The active layer and grating layer were grown by the first step MOVPE. The DFB LD and the optical isolator section have the same InGaAsP compressively strained multiple quantum well (MQW) active layers. The MQW is composed of 14 compressively strained (+0.7%) quantum wells and 15 tensile strained (-0.4%) InGaAsP barriers. The MQW active layer is sandwiched by 50nm-thick InGaAsP separated confinement heterostructure (SCH)

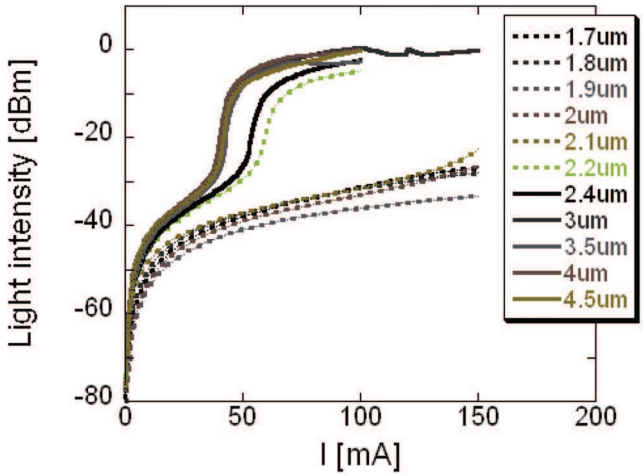

Fig. 3. Light output – current charactristics of TE mode semiconductor active waveguide optical isolators with waveguide width w of 1.7-4.5μm. Measurement temperature is 15°C.

layers. The photoluminescence peak wavelength of the MQW active layer was set at 1540nm. The InGaAsP index-coupled grating layer thickness is 20nm. The p-InP spacer layer thickness between the upper InGaAsP SCH layer and the grating layer is 50nm. A grating is defined by electron-beam lithography in DFB LD section. After the InGaAsP grating formation by wet chemical etching, 1μm-thick p-InP upper cladding layer and p^+InGaAs contact layer were grown by the second step MOVPE. The deep-etched waveguides were fabricated by Cl_2/Ar reactive ion etching, as shown in Fig. 1. The waveguide widths were

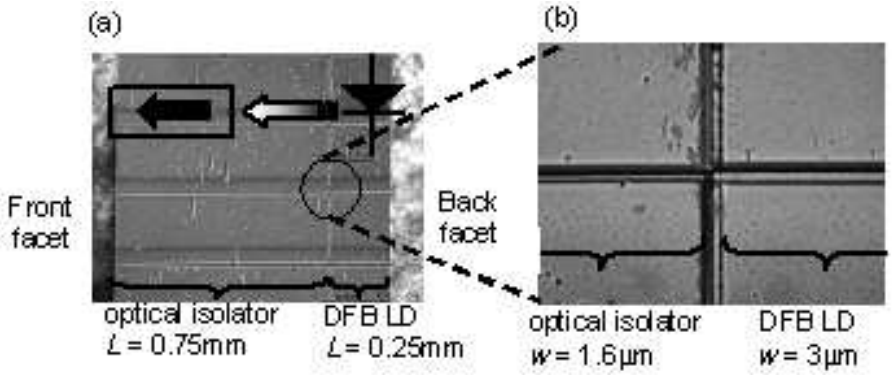

Fig. 4. Top views of the fabricated device bar with three integrated devices of waveguide optical isolators and DFB LDs by an optical microscope. (a) is the whole image and (b) is the magnified image of the optical isolator / DFB LD junction. Three horizontal waveguide stripes in (a) are corresponding to three integrated devices. The vertical line is a 5μm-width electrode separation region. L and w denote the device length and waveguide stripe width. The distance between the adjacent waveguide stripes is 250μm.

3μm for DFB LDs and 1.6μm for waveguide optical isolators. The tapered waveguide region where the waveguide width w gradually changes, is 10μm-long. Fig. 4 shows the top views of the integrated devices taken by an optical microscope. The basic fabrication process including the waveguide stripe formation, and the ferromagnetic / electrode metal deposition, is the same as that of previous discrete TE mode semiconductor active waveguide optical isolators (Shimizu & Nakano, 2004, 2006). The Ti/Au top electrodes and p^+InGaAs contact layers of the DFB LD / optical isolator sections are separated by each other, as shown in Fig. 4(b). The electrical isolation resistance between the two top electrodes is 1-5kΩ. It should be stressed that unlike conventional free space optical isolators, no polarizers are needed between the DFB LD and the optical isolator section. The device facets are as cleaved for the characterizations in this paper.

3. Characterizations

We measured the emission spectra of the integrated devices from the front and back facets under permanent magnetic fields of +/-0.1T and 0T. The front and back facets correspond to the optical isolator and the DFB LD sides, respectively (Fig. 4). The front facet emission is from the DFB LD with propagating through the waveguide optical isolator. The back facet emission is the direct emission from the DFB LD without propagating through the waveguide optical isolator. Fig. 5 shows the emission spectra by an optical spectrum analyzer from the (a) front and (b) back facets of the integrated devices under permanent magnetic fields of +/-0.1T and 0T. The emitted light was coupled by lensed optical fibers. The bias currents are 90 and 150mA for the DFB LD and active waveguide optical isolator, respectively. The threshold current of the DFB LD is larger than 40mA. The fabricated chips were kept at 15°C. The DFB LDs showed single mode emissions with λ = 1543.8nm. A 4dB emission intensity change was observed for waveguide-optical-isolator-propagated DFB LD light under magnetic field of +/-0.1T as shown in Fig. 5(a). On the other hand, such intensity change was much smaller (0.4dB) for the back facet emission, as shown in Fig. 5(b). These results show that the waveguide-optical-isolator- propagated DFB LD light received the nonreciprocal loss. Therefore, this is the first demonstration of monolithic integration of the semiconductor active waveguide optical isolators with DFB LDs. Although the output light intensity of the waveguide optical isolator is weak (-56dBm), an anti-reflection (AR) coating at the front facet, and a high-reflection (HR) coating at the back facet could enhance the output intensity. Also, the optical reflection at the tapered waveguide region brings the internal reflections along the DFB LD section, which leads to weak output intensity. By solving these issues, the output intensity can be improved and the optical isolation can be enhanced with the Fe layer closer to the active layer. At this stage, maximum optical isolation is 14.7dB/mm for discrete TE mode semiconductor active waveguide optical isolators (Shimizu & Nakano, 2006).

4. Conclusion

We have demonstrated monolithic integration of the semiconductor active waveguide optical isolators with DFB LDs. By controlling the waveguide width of the TE mode semiconductor active waveguide optical isolators, we established simple monolithic

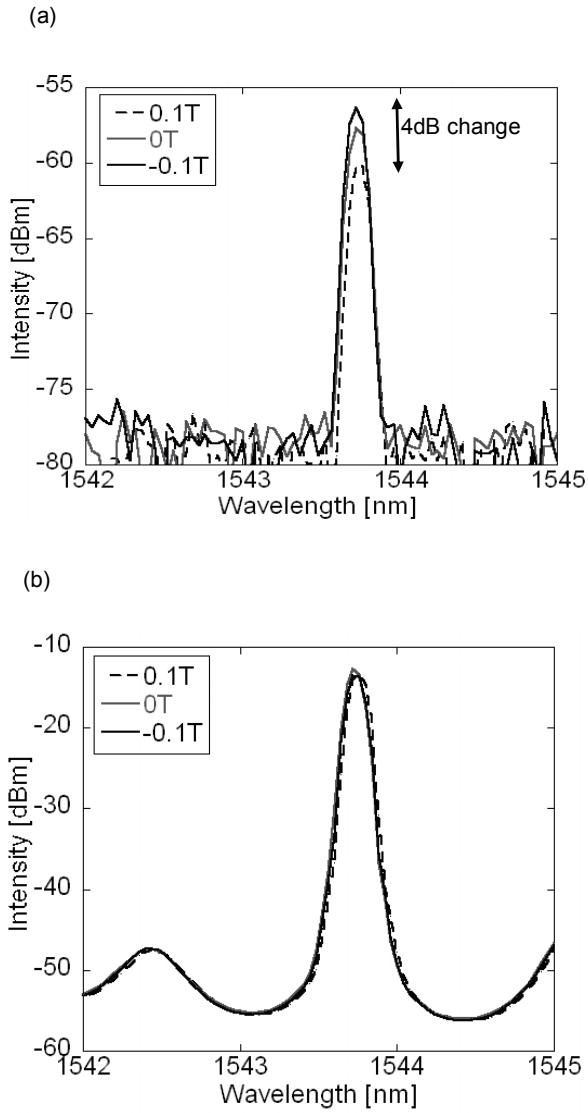

Fig. 5. Emission spectra of the integrated device from the (a) front and (b) back side facets under the permanent magnetic field of +/-0.1T and 0T. Note that the three curves in (b) are almost overlapped.

integration process of the waveguide optical isolators with DFB LDs. The integrated devices showed a single mode emission at λ = 1543.8nm and 4dB optical isolation. Although the optical isolation is smaller than commercially available "free space" optical isolators at this stage, this is the first step towards monolithically integrated isolator-DFB LD devices.

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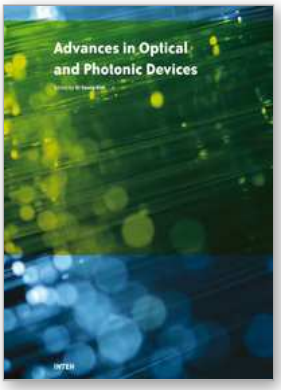

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The title of this book, Advances in Optical and Photonic Devices, encompasses a broad range of theory and applications which are of interest for diverse classes of optical and photonic devices. Unquestionably, recent successful achievements in modern optical communications and multifunctional systems have been accomplished based on composing “building blocks” of a variety of optical and photonic devices. Thus, the grasp of current trends and needs in device technology would be useful for further development of such a range of relative applications. The book is going to be a collection of contemporary researches and developments of various devices and structures in the area of optics and photonics. It is composed of 17 excellent chapters covering fundamental theory, physical operation mechanisms, fabrication and measurement techniques, and application examples. Besides, it contains comprehensive reviews of recent trends and advancements in the field. First six chapters are especially focused on diverse aspects of recent developments of lasers and related technologies, while the later chapters deal with various optical and photonic devices including waveguides, filters, oscillators, isolators, photodiodes, photomultipliers, microcavities, and so on. Although the book is a collected edition of specific technological issues, I strongly believe that the readers can obtain generous and overall ideas and knowledge of the state-of-the-art technologies in optical and photonic devices. Lastly, special words of thanks should go to all the scientists and engineers who have devoted a great deal of time to writing excellent chapters in this book.

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