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# Semiconductor / Ferromagnetic Metal Hybrid Optical Isolators using Nonreciprocal Polarization Rotation

Hiromasa Shimizu, Syunsuke Goto, and Toshiaki Mori

Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology,
2-24-16 Naka-cho, Koganei, Tokyo, 184-8588, Japan
Phone: +81-42-388-7996 E-mail: h-shmz@cc.tuat.ac.jp

## 1. Introduction

Optical isolators are indispensable devices to protect semiconductor laser diodes (LDs) from unwanted reflected light. Semiconductor waveguide optical isolators have been awaited for monolithic integration with LDs. Semiconductor optical isolators based on nonreciprocal loss have been reported [1, 2]. Such isolators are composed of semiconductor optical amplifier (SOA) waveguides with ferromagnetic metals. Transversely magnetized ferromagnetic metal provides nonreciprocal loss due to the transverse magneto-optic Kerr effect. The forward propagation loss from the ferromagnetic metal is compensated for by the SOA gain, whereas the larger propagation loss for the backward traveling light is not fully compensated for, thus realizing optical isolator operation, as shown in Fig. 1. Fe-InGaAsP/InP semiconductor active waveguide optical isolators having isolation of 14.7 dB/mm have been reported [1], and FeCo-InGaAlAs/InP semiconductor active waveguide optical isolators having isolation of 6 dB/mm and zero propagation loss, have been demonstrated [2]. Furthermore, monolithic integration with distributed feedback laser diodes has also been realized [3]. Above semiconductor optical isolators show 5-15 dB/mm class optical isolation. Since the optical isolation is proportional to the device length, longer (> 2 mm) devices are necessary to realize 10-20 dB class optical isolation. In order to increase the optical isolation in semiconductor active waveguide optical isolators based on nonreciprocal loss, the device must be lengthened or the magneto-optic effect must be enhanced. A stronger magneto-optic effect can be obtained by decreasing the distance between the ferromagnetic metal and the waveguide core layer. However, this approach leads to larger forward propagation loss due to the ferromagnetic metals, and hence, a larger SOA gain is necessary to fully compensate for the forward propagation loss. Therefore, with nonreciprocal loss, the optical isolation cannot be increased in a straightforward manner.

On the other hand, waveguide optical isolators based on a nonreciprocal phase shift have been demonstrated in Mach-Zehnder interferometeric waveguides with ferrimagnetic garnet such as $CeY_2Fe_5O_{12}$. Ferrimagnetic garnet substrates have been directly bonded on InGaAsP/InP [4], and silicon on insulator (SOI) waveguides [5]. Optical isolation based on a nonreciprocal phase is not proportional to the device length, and useful to realize 10-20 dB class optical isolation in semiconductor optical isolators [6], although interferometric waveguides are necessary. In this paper, we report Fe-InGaAlAs/InP semiconductor optical isolators based on nonreciprocal polarization rotation. We demonstrated 18.3 dB optical isolation in a 0.85mm-long device using polarization dependence of the nonreciprocal phase shift in an Fe-InGaAlAs/InP waveguide and a polarizer, without fabricating Mach-Zehnder interferometeric waveguides.

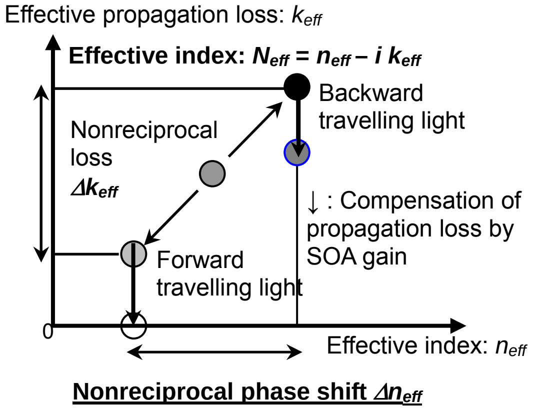

Fig. 1 A schematic illustration of nonreciprocal propagation (phase shift $\Delta n_{eff}$ and loss $\Delta k_{eff}$) in semiconductor optical isolators.

## 2. Operation Principle

The configuration of the optical isolation based on nonreciprocal polarization rotation is schematically illustrated in Fig. 2. We used transverse magnetic (TM) mode semiconductor optical isolators. Magnetic field was applied perpendicular to the waveguide and in plane (Voigt configuration). Note that the nonreciprocal polarization rotation is not Faraday rotation. Fig. 2 illustrates the change of polarization state of the input light by nonreciprocal phase shift for TM mode. Since the

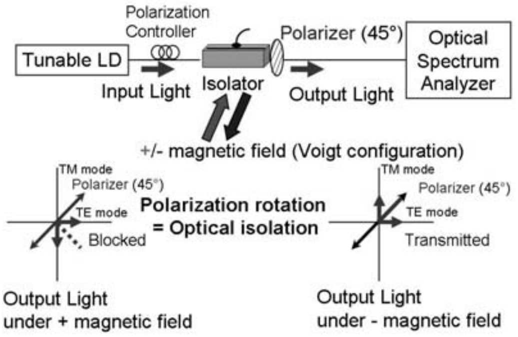

Fig. 2 Principle and measurement setup of semiconductor optical isolators using nonreciprocal polarization rotation.

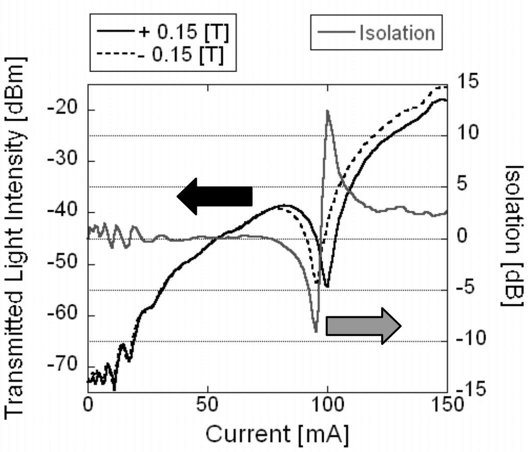

Fig. 3 Current dependences of the transmitted light intensity and optical isolation under magnetic field of + / - 0.15 T. The wavelength of the incident light is 1295 nm.

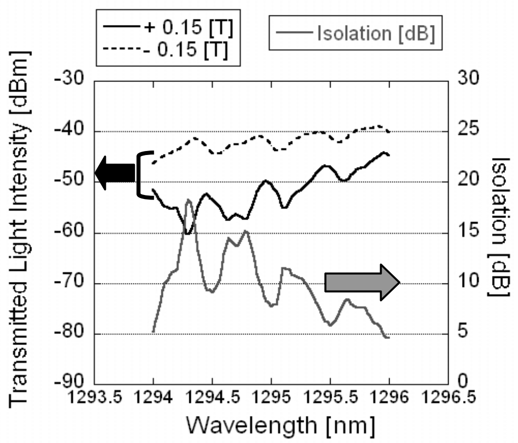

Fig. 4 Wavelength dependences of the transmitted light intensity and optical isolation under magnetic field of + / - 0.15 T. The bias current is 100mA.

nonreciprocal phase shift is not obtained for transverse electric (TE) mode, the change of polarization state is dependent on magnetic field direction. When + magnetic field is applied the output light from the Fe-InGaAlAs/InP waveguide, the output light is linearly polarized at -45$^o$ with respect to the x axis, and cut-off by the polarizer (+45$^o$). When – magnetic field is applied, the polarization state of the output light changes owing to the difference of the effective refractive index between the TE-mode light and TM- mode light, thus permitting output light allowing the output light through the polarizer, and realizing optical isolator operation. The nonreciprocal phase shift of π brings an infinite extinction ratio, when the nonreciprocal propagation loss is negligible.

## 3. Experimental Results

Semiconductor optical isolators used in this study are as-cleaved 0.85mm-long TM-mode Fe-InGaAlAs / InP SOA waveguide devices which have the gain peak wavelength of 1295 nm, nonreciprocal loss of 3.0 dB/mm for TM-mode light. The devices were kept at 15$^o$C, and magnetic field of +/-0.15 T was applied by an electromagnet. An incident light was from tunable LD light of the wavelength of 1295 nm and intensity of 0 dBm. A polarization controller was adjusted so as to minimize the transmission light through the polarizer under bias current of 100 mA and magnetic field of +0.15 T, so that high extinction ratio can be obtained. The output light was measured with an optical spectrum analyzer (OSA).

Fig. 3 shows the bias current dependences of the transmitted light intensity and optical isolation for the input light wavelength of 1295 nm under magnetic field of + / - 0.15 T. Since the Fe-InGaAlAs/InP waveguide devices are active devices, the refractive index is dependent on the bias current and the transmitted light intensity through the polarizer is influenced by the bias current. At the bias current of 100mA, optical isolation of as large as 12.4 dB was observed. Fig. 4 shows the wavelength dependences of the transmitted light intensity and optical isolation under magnetic field of + / - 0.15 T and bias current of 100 mA. The Fabry-Perot resonances were observed, because the facets are as cleaved. The highest optical isolation was 18.3 dB at the wavelength of 1294.3 nm. The nonreciprocal phase shift is calculated to be 0.24 π/mm from Fig. 4. By optimizing the ferromagnetic materials, larger nonreciprocal phase shift can be obtained, thus producing a larger optical isolation. A polarizer and polarization converters are necessary instead of Mach-Zehnder interferometeric waveguides in this study. The polarization manipulating technologies in InP waveguides are currently developing [7], and will enable the semiconductor optical isolators in this study.

## 4. Conclusions

We have developed semiconductor optical isolators based on nonreciprocal polarization rotation. Optical isolation higher than 18.3 dB was observed in 0.85 mm-long Fe-InGaAlAs/InP waveguides. Semiconductor optical isolators in this study are suitable to realize large optical isolation with short (<1 mm) device length.

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