# An Integrated Optical Waveguide Isolator Based on Multimode Interference by Wafer Direct Bonding

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***Abstract*—An integrated waveguide optical isolator based on multimode interference (MMI) by wafer direct bonding has been studied. It was found that wafer direct bonding between InP and $Gd_3Ga_5O_{12}$ (GGG) is effective for the integration of a waveguide optical isolator. The isolation ratio was found to be 2.9 dB in the proposed device.**

***Index Terms*—Garnet, multimode interference, optical isolator, wafer direct bonding.**

## I. Introduction

In optical communication systems, an optical isolator is of great importance in order to protect active devices from unwanted reflected light and to stabilize oscillation of a semiconductor laser diode. An optical waveguide isolator has been strongly required for the integration of the other optical components. Furthermore, its realization is expected to reduce cost and component size of such devices.

In particular, the application of multimode interference (MMI) effect based on self-imaging principle is believed to make it possible to realize optical devices embodying attractive features such as very small device dimensions and easy fabrication. The use of nonreciprocal phase shift in an optical waveguide isolator has an advantage that phase matching is not necessary between two orthogonally polarized modes and complicated control of magnetization, which generally are required in mode conversion optical isolator [1]–[4]. Magnetic garnet films such as $\mathrm{CeY_2Fe_5O_{12}}$ (Ce:YIG; Ce-substituted yttrium iron garnet) are suitable for an integrated optical waveguide isolator because of their large Faraday rotation and low optical loss at 1.3 and 1.55 $\mu$m, respectively. It is well-known that Faraday rotation is a primary factor for nonreciprocal phase shift.

In the present work, the authors report on a novel integrated optical waveguide isolator based on MMI by wafer direct bonding between the InGaAsP and Ce:YIG under a magnetic field, exhibiting the possibility to work as an isolator. The optical isolation ratio of the fabricated device will be discussed.

## II. Device Structure

The nonreciprocal phase shifter consists of a triple-layered slab optical waveguide with a magnetooptic cladding layer and a semiconductor guiding layer. The schematic diagram of the nonreciprocal phase shifter is shown in Fig. 1. In order to realize an integrated optical waveguide isolator using nonreciprocal phase shift, a magnetic field should be applied transverse to the light propagation along the $z$-direction and is on the film plane. On the assumption that the materials of the waveguide are lossless, the gyrotropic relative permittivity tensor $[\kappa]$ for magnetooptic cladding layer can be written as

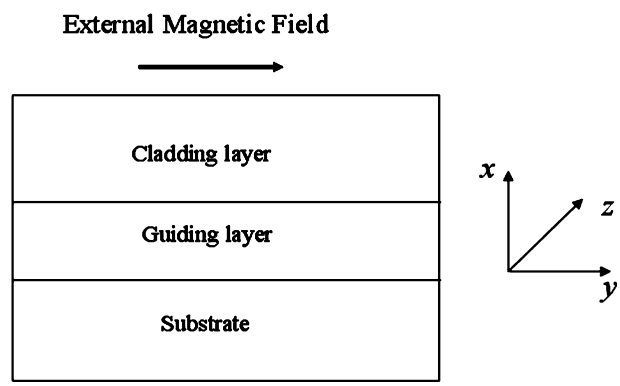


Fig. 1. Schematic diagram of the triple-layered slab optical waveguide with a magnetooptic cladding layer.

$$[\kappa] = \begin{pmatrix} \kappa_0 & 0 & 0 \\ 0 & \kappa_0 & 0 \\ 0 & 0 & \kappa_0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & i\xi \\ 0 & 0 & 0 \\ -i\xi & 0 & 0 \end{pmatrix}. \quad (1)$$

The off-diagonal component can be expressed by $\xi = 2\sqrt{\kappa_0}\Theta_F/k_0$, where $\kappa_0$, $\Theta_F$, $k_0$ are the dielectric constant, specific Faraday rotation, and vacuum wave number, respectively.

The magnitude of the propagation constants of transverse magnetic field (TM) modes differs depending on the light propagation direction with the magnetooptic configuration. However, the magnitude of the propagation constants of transverse electric field (TE) modes is independent of the light propagation direction [5]. Therefore, only TM modes traveling optical waveguide experience nonreciprocal phase shift due to Faraday rotation.

A schematic diagram of the fabricated integrated optical isolator is shown in Fig. 2. The width and length of multimode section are 30 and 1967 $\mu$m, respectively. The width of input and output waveguide is 4 $\mu$m and the height of InGaAsP(1.25Q) is 0.44 $\mu$m. The layer structure of the MMI section of the optical isolator is Ce:YIG/InGaAsP/InP, and that of the input and output

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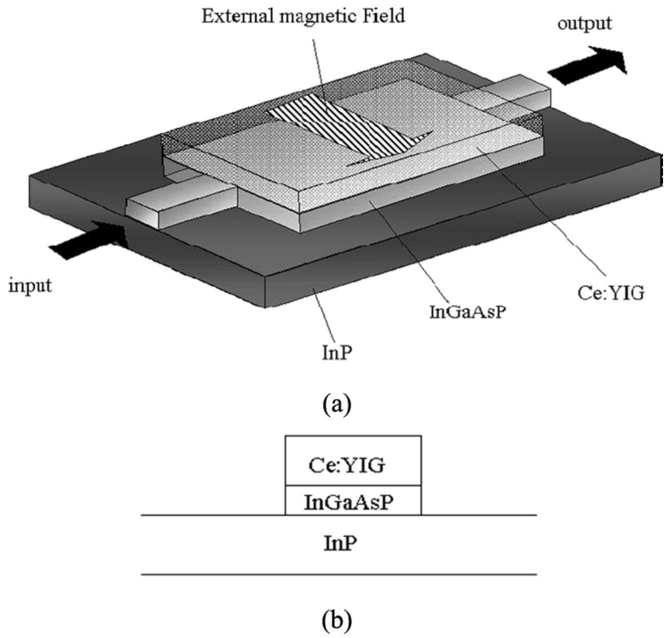


Fig. 2. (a) Schematic diagram of an optical isolator with an MMI section. (b) Cross-sectional view of an MMI section.

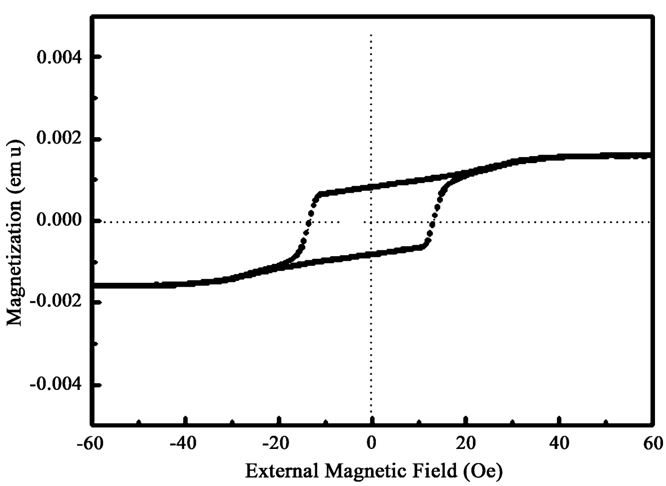


Fig. 3. Hysteresis loop of the Ce:YIG obtained using a VSM.

of the device is air/InGaAsP/InP. A wafer direct bonding technique has been employed in order to construct the optical waveguide isolator for monolithic integration with other optical components. The cladding layer, Ce:YIG, was bonded to the MMI section with the InGaAsP guiding layer.

## III. Experiment

The Ce:YIG layer was prepared by radio frequency (RF) sputtering on a (111)-oriented (Ca, Mg, Zr)-doped $\mathrm{Gd_3Ga_5O_{12}}$ (NOG) substrate in the range of 660–680 °C. An Ar and $O_2$ mixture gas was used for sputtering, and its pressure was $2.0 \times 10^{-2}$ torr. Fig. 3 shows the hysteresis loop of the sample using a vibrating sample magnetometer (VSM), obtained when a magnetic field was applied along the in-plane direction at room temperature. The specific Faraday rotation of Ce:YIG was measured to be $-4500^\circ/\mathrm{cm}$ at a wavelength of 1.55 $\mu$m.

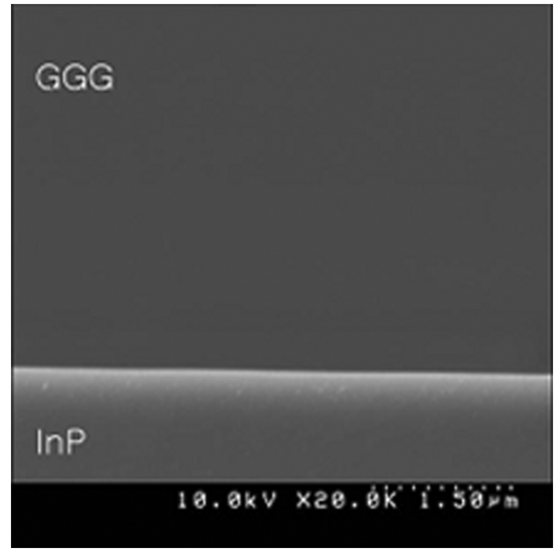


Fig. 4. Cross-sectional scanning electron microscope (SEM) image of bonded sample between InP and GGG.

Prior to bonding between InGaAsP and Ce:YIG, the bonding between InP and a commercially available mirror polished $\mathrm{Gd_3Ga_5O_{12}}$ (GGG) has been investigated. The crystallographic property of InP and GGG is similar to that of InGaAsP and Ce:YIG, respectively. The InP and GGG were cleaned using trichloroethylene, acetone, and methanol in order. After cleaning, the surfaces of the InP and GGG wafer were treated by $O_2$ plasma for 30 s at 100 W RF power under 0.3 torr for surface activation to accomplish direct bonding. Bonding between InP and GGG was strengthened by heat treatment at 220 °C in Ar for 120 min. Fig. 4 shows a cross-sectional image of the bonded wafer between the InP and GGG. The wafer direct bonding was found to be successfully performed without an air gap between the bonded layers. An air gap between the magnetic garnet film and semiconductor layer is well known to give rise to the rapid reduction of nonreciprocal phase shift for an integrated optical waveguide isolator [6]. The same bonding process has been adopted for the bonding between InGaAsP and Ce:YIG layer.

## IV. Results and Discussion

In order to obtain optical isolation, a magnetic field was applied along the MMI section of the optical isolator. The direction of the magnetic field was transverse to the light propagation and was on the film plane. When a wave travels in the multimode waveguide, the input field profile is reproduced in single or multiple images at periodic intervals along the waveguide. The length of the MMI to get a self-image of an input field is determined by the beat length $\mathrm{L}_\pi$ obtained from the two lowest order modes [7], [8]

$$L_\pi \equiv \frac{\pi}{\beta_0 - \beta_1} \tag{2}$$

where $\beta_0$ and $\beta_1$ are propagation constant of fundamental mode and first-order mode, respectively.

Under the magnetic field, the nonreciprocal phase shift occurs in the TM modes traveling in the MMI section with a magnetooptic cladding layer. As a consequence, the beat lengths of the

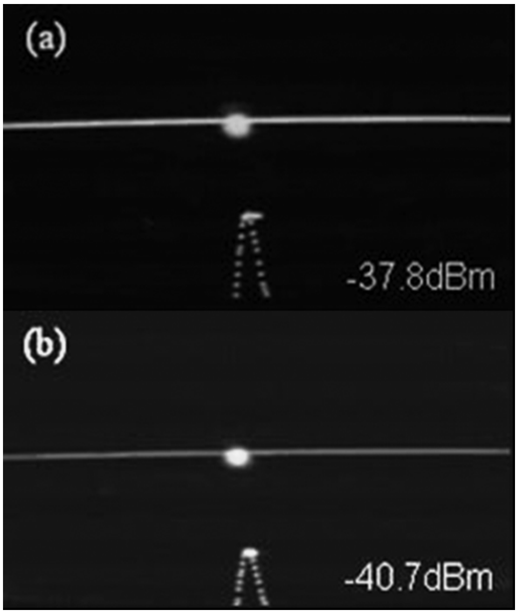


Fig. 5. Near-field pattern and intensity of output from an optical isolator for (a) a forward direction and (b) a backward direction.

forward- and backward-traveling wave are different. From the above-mentioned reason, it is expected that the focus lengths to get a single image of an input field profile are different for forward and backward propagation direction. The focus length of a forward-traveling wave is to be determined when maximum output intensity is obtained, whereas the focus length of a backward-traveling wave is located at the input waveguide of the MMI section imprecisely. It makes the output of backward-traveling wave get relatively smaller intensity than that of the forward-traveling wave. Therefore, this device is able to act as an optical isolator.

In order to measure optical isolation ratio, TM polarized light passing through a polarization controller from a tunable laser diode was coupled with the input waveguide of the optical isolator. The guided optical field pattern at the cleaved output facet was displayed on a television (TV) monitor using an objective lens and an infrared camera. Then a Ge photodetector placed behind an adjustable aperture, which can eliminate scattered light, was used to measure the output intensity. A magnetic field was applied along the device fabricated using wafer direct bonding between InGaAsP and Ce:YIG.

A permanent magnet was utilized to saturate Ce:YIG cladding layer. The isolation ratio was measured through the variation of the intensity by reversing an external magnetic field direction, since reversing the direction of the magnetic field is equivalent to reversing the wave propagating direction. The near-field patterns and intensities of the outputs for forward and backward directions are shown in Fig. 5. For the forward and backward directions, the intensities were measured to be −37.8 and −40.7 dBm, respectively, demonstrating the integrated optical waveguide isolator with a $1 \times 1$ MMI section using a wafer direct bonding technique. The isolation ratio was found to be 2.9 dB. The isolation ratio is believed to be increased by optimizing direct bonding conditions, giving rise to the enhanced bonding strength between InGaAsP and Ce:YIG and reduction of possibility of locally induced air gap in whole bonding area.

## V. Conclusion

An integrated waveguide optical isolator based on multimode interference (MMI) by wafer direct bonding has been investigated. The device consists of a $1 \times 1$ MMI section with a $\mathrm{CeY_2Fe_5O_{12}}$ (Ce:YIG) cladding layer. The wafer bonding process between InP and $\mathrm{Gd_3Ga_5O_{12}}$ (GGG) is effective for the integration of an optical waveguide isolator. The measured isolation ratio was 2.9 dB in the proposed device. The isolation ratio can be increased by improving direct bonding conditions and designs of the MMI section.

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