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A Magneto-Optic Waveguide Isolator Using Multimode Interference Effect

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We have investigated an optical waveguide isolator with a multimode interference section by wafer direct bonding, operating at a wavelength 1.55 μm. In order to fabricate the device for monolithic integration, the wafer direct bonding between a magnetic garnet material as a cladding layer and a semiconductor guiding layer has been achieved. We found that wafer direct bonding between InP and GGG ($Gd_3Ga_5O_{12}$) is effective for the integration of a waveguide optical isolator. The isolation ratio was obtained to be 2.9 dB in the device.

Key words : optical isolator, multimode interference, nonreciprocal phase shift, wafer bonding

1. Introduction

An optical isolator is a device that allows the propagation of light in one direction, and it is of great importance to protect active devices such as a laser diode and an optical amplifier from unwanted reflected signals for optical communication systems. The integrated optical isolators are highly required for the integration with optoelectronic devices and, in particular, indispensable to realize photonic integrated circuits (PICs) ultimately. In recent years, isolators and circulators employing nonreciprocal phase shift have been investigated because it needs not phase mismatching between two orthogonally polarized modes and complicated control of magnetization [1-5]. The application of multimode interference (MMI) effect, based on self-imaging principle, makes it possible to realize optical devices with promising characteristics such as ultra compact device dimensions and ease of fabrication. Magnetic garnet films such as Ce:YIG (Ce-substituted yttrium iron garnet) with good crystal quality are suitable for an integrated optical waveguide isolator because of their large Faraday rotation and low optical loss at wavelengths of 1.3 μm and 1.55 μm.

In this study, we report on an integrated optical isolator with 1 × 1 MMI section with a magneto-optic cladding layer. For the purpose of monolithic integration, the wafer direct bonding between InGaAsP and Ce:YIG has been used. By virtue of this configuration, the device plays its role as an optical isolator under an external magnetic field. The optical isolation ratio of the fabricated device will be discussed.

2. Basic theory and Device structure

The nonreciprocal phase shifter consists of a triple-layered slab optical waveguide with a magneto-optic cladding layer and a semiconductor guiding layer. The basic structure is shown in Fig. 1. In order to realize integrated optical waveguide isolator using nonreciprocal phase shift, an external magnetic field is applied transverse to the light propagation along z-direction and is on the film plane. Based on the assumption that the materials of the waveguide are lossless, the gyrotropic relative permittivity tensor for magneto-optic cladding layer can be written as

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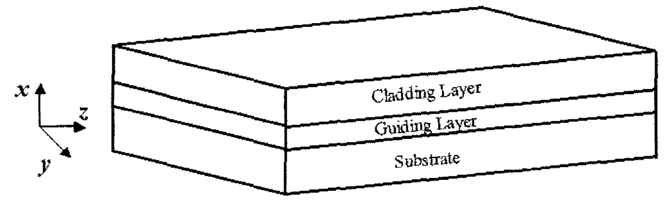

Fig. 1. A basic structure of the tripled-layered slab optical waveguide with a magneto-optic cladding layer.

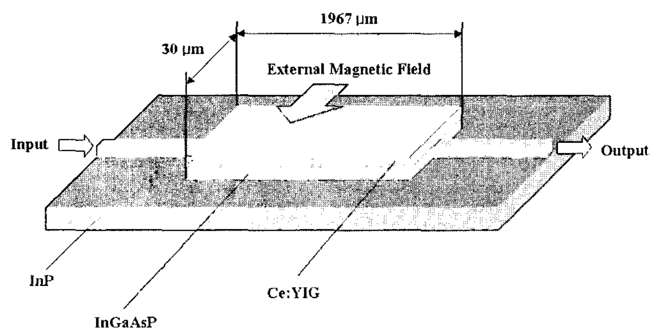

Fig. 2. A schematic layout of an optical isolator with a multimode interference (MMI) section.

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

The off-diagonal component can be expressed by $\xi = 2\sqrt{\kappa_o}\Theta_F/\kappa_o$, where κ_o, Θ_F, κ_o are the dielectric constant, specific Faraday rotation, and vacuum wave number, respectively. ξ is assumed to be constant along cladding layer.

The magnitude of the propagation constants of TM (Transverse Magnetic Field) modes differs depending on a light propagation direction with the magneto-optic configuration. However, the magnitude of the propagation constants of TE (Transverse Electric Field) modes is independent of a light propagation direction [6]. Therefore, only TM modes traveling optical waveguide experience nonreciprocal phase shift due to Faraday rotation.

Fig. 2 shows a schematic layout of the fabricated optical isolator. The width and length of multimode section are 30 μm and 1967 μm, respectively. The width of input and output waveguide is 4 μm and the thickness of InGaAsP(1.25Q) is 0.44 μm. The layer structure of MMI section of the optical isolator is Ce:YIG/InGaAsP/InP, and that of the input and output 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 upper cladding layer, Ce:YIG was bonded to the InGaAsP guiding layer of MMI section.

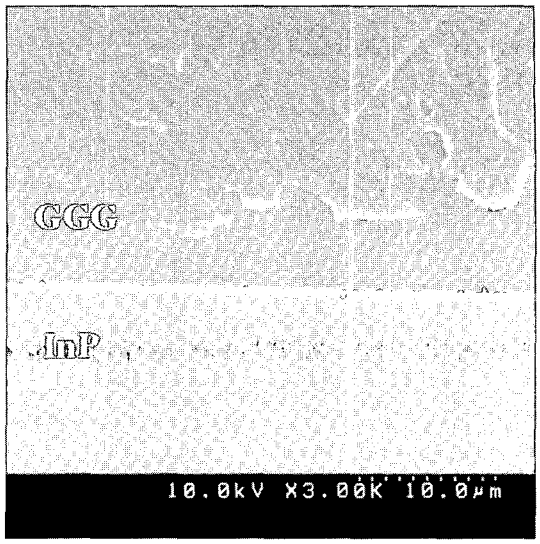

Fig. 3. Cross sectional SEM image of bonded sample between InP and GGG ($Gd_3Ga_5O_{12}$).

3. Experiment

The $CeY_2Fe_5O_{12}$ (Ce:YIG) layer was prepared on a (111)-oriented NOG [(Ca, Mg, Zr)-doped $Gd_3Ga_5O_{12}$] substrate with a deposition rate 2.4 nm/min in a sputtering gas pressure of 2.0×10^{-2} Torr mixed with Ar and O_2. The incident RF power was 50W. The specific Faraday rotation of Ce:YIG was measured to be 4500°/cm at a wavelength 1.55 μm.

Before bonding between InGaAsP and Ce:YIG, the bonding between InP and a commercially available mirror polished GGG($Gd_3Ga_5O_{12}$) 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 seconds 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. 3 shows a cross sectional image of the bonded wafer InP and GGG. The wafer direct bonding was found to be successfully performed without an air gap between the bonded layers from the Fig. 3. An air gap between the magnetic garnet film and semiconductor layer brings about the rapid reduction of nonreciprocal phase shift for an integrated optical waveguide isolator [7]. In order to accomplish bonding between InGaAsP and Ce:YIG for fabrication of device, the same bonding process has been adopted.

4. Results and Discussion

The length of multimode interference section to get a self-image of an input field is determined by propagation constants of fundamental mode and first-order mode [8-9]. A unidirectional external magnetic field is applied to the Ce:YIG cladding layer in the MMI section of the device. The direction of the magnetic field is transverse to the light propagation and is on the film plane. The TM modes traveling in MMI section with a magneto-optic layer experience nonreciprocal phase shift. Therefore, the focus lengths to get self-image are expected to be different for forward and backward propagation direction. The focus length of forward traveling wave is to be set to obtain maximum output intensity, while that of backward traveling wave is located at the input waveguide of MMI section imprecisely. It makes the output of backward traveling wave have relatively smaller intensity than that of forward traveling wave. By above reason, this device can act as an optical isolator.

In order to measure isolation ratio at a wavelength of 1.55 μm, TM polarized light passing through a polarization controller from a tunable laser diode was coupled to the input waveguide of optical isolator. The guided optical field pattern at the cleaved output facet was displayed on a TV monitor by use 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 output intensity. An unidirectional external magnetic field was applied to the device fabricated using wafer direct bonding between InGaAsP and Ce:YIG using permanent magnet. The isolation ratio was obtained through the variation of the intensity by reversing an external magnetic field direction, because the 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 direction are shown in Fig. 4. The measured intensities were –37.8 dBm and –40.7 dBm for forward and backward propagating direction, respectively. It demonstrates the integrated optical waveguide isolator with 1 × 1 MMI section using a wafer direct bonding technique. The isolation ratio was found to be 2.9 dB.

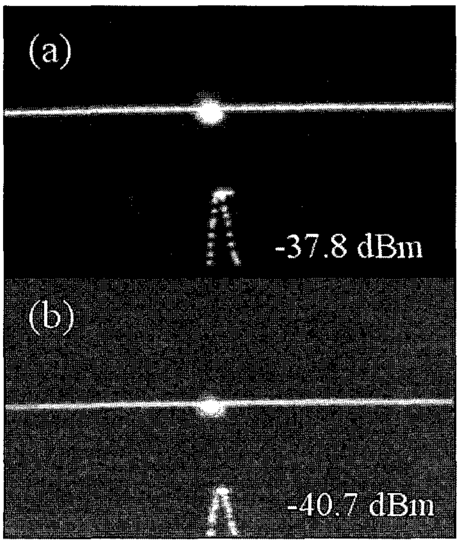

Fig. 4. The measured near field pattern and intensity of output from an optical isolator for (a) forward direction (b) backward direction.

5. Conclusion

An integrated optical waveguide isolator based on multimode interference effect has been investigated. The device consists 1×1 multimode interference section with Ce:YIG cladding layer by wafer direct bonding. The wafer bonding process between InP and GGG is effective for the monolithic integration of an optical waveguide isolator. The isolation ratio was found to be 2.9 dB. The isolation ratio can be further increased by enhancing direct bonding conditions and designs of multimode interference section.

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