TM mode optical waveguide isolator with 8.8 dB/mm nonreciprocal propagation induced by ferromagnetic MnAs

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Abstract: A 1540 nm, TM mode waveguide isolator based on the nonreciprocal loss shift was developed. It consisted of a semiconductor waveguide with a ferromagnetic MnAs layer and showed an isolation ratio of 8.8 dB/mm.

OCIS codes: (230.3810) Magneto-optical devices; (250.5980) Semiconductor optical amplifiers;

1 Introduction

An important element for developing photonic integrated circuits is waveguide isolators that can be monolithically combined with other waveguide devices such as lasers, optical amplifiers, and switches. It is desirable that the isolators are polarization-insensitive, i.e., operative or usable regardless of the polarization of light, at a wavelength of 1550 nm. One promising way of creating such waveguide isolators is by using of nonreciprocal loss shift, a magneto-optic phenomenon where——in an optical waveguide with a magnetized metal layer——the propagation loss of light is larger in backward than in forward propagation [1,2]. Using this phenomenon can provide new waveguide isolators that use neither Faraday rotator nor polarizer and, therefore, are suitable for monolithic integration with other devices on a semiconductor subatrate [3-5]. To creat polarization-insensitive waveguide isolators, we are developing a combination of TE mode and TM mode isolators based on this nonreciprocal phenomenon. We built a prototype of a 1550 nm, TE mode isolator, consisting of a semiconductor optical amplifier and a ferromagnetic Fe layer, and obtained an isolation ratio of 14.7 dB/mm——the largest value ever reported for waveguide isolators [3]. In addition to this result, we fabricated a TM mode waveguide isolator with a ferromagnetic MnAs layer grown epitaxially and obtained an 8.8 dB/mm isolation ratio at a wavelength of 1540 nm. The following sections provide the details on this TM mode isolator.

2 Device structure

Figure 1(a) shows the structure of our TM mode waveguide isolator. It consists of a TM mode semiconductor optical amplifier (SOA) covered with a ferromagnetic MnAs layer. An Au/Ti double metal layer covers the MnAs layer, forming an electrode to send driving current to the SOA. Light passes through the SOA perpendicular to the figure (z direction).

To operate the device, an external magnetic field is applied so that the MnAs layer will be magnetized perpendicular to the propagation of light, as indicated by the arrow in the figure (x direction). This produces a difference in propagation loss of TM-polarized light between forward (z direction) and backward propagation (-z direction); the propagation loss is larger for backward propagation than for forward (see Fig. 1(b)). This nonreciprocal loss shift is caused by the magneto-optic transverse Kerr effect. The SOA compensates for the forward propagation loss; it is operated so that the net loss for forward propagation will be zero. Under these conditions, the device can act as an optical isolator.

The point of our device is its use of MnAs as a ferromagnetic material, instead of metals such as Fe and Ni. In this device structure, which is necessary for TM mode operation, the ferromagnetic layer to produce the magneto-optic effect is also used as a contact to send a driving current to the SOA. This means that the ferromagnetic layer has to meet a dual requirement of producing a large magneto-optic effect and of providing a low-resistive ohmic contact for the InGaAsP contact layer. Ordinary ferromagnetic metals are not suited for this purpose; e.g., a Fe layer produces a large magneto-optic effect but produces a high Schottky barrier on InGaAsP semiconductors, whereas a Ni layer can provide a low Schottky barrier but produces a small magneto-optic effect. In addition, during a contact annealing, they produce undesirable nonferromagnetic materials such as FeAs and NiAs at the contact interface; this reduces nonreciprocal loss shift in the device. To solve these problems, we used MnAs for the ferromagnetic layer. MnAs is a ferromagnetic, intermetallic compound with a nickel-arsenide structure and can be grown epitaxially on GaAs, InP, and related semiconductors [6]. MnAs produces a large magneto-optic effect comparable with Fe layers and produce no Schottky barrier on InGaAsP semiconductors.

We designed a sample device to operate at a wavelength of 1520-1560 nm and fabricated the device as follows. The SOA region was grown with metal-organic vapor phase epitaxy (MOVPE). The MQW was composed of five tensile-strained InGaAs quantum wells (-0.4 %, 13 nm) and six compressive-strained InGaAlAs barriers (+0.6 %, 8 nm, λ_g = 1.2 um). The p-type InP cladding layer and the p-type InGaAsP contact layer were 0.25 um and 0.15 um thick. A 100 nm MnAs layer was grown epitaxially on the contact layer with molecular-beam epitaxy (MBE). After that, a SiO_2 layer was deposited on the MnAs layer with magnetron sputtering, and a stripe window of 5.5 um width was opened with wet chemical etching. A 100 nm Ti layer and a 200 nm Au layer were then deposited on the surface to make an electrode, using electron-beam evaporation. Finally, both ends of the device were cleaved to set the device length to 0.6 mm. Figure 2 is a cross section of the device observed with a scanning electron microscope (SEM).

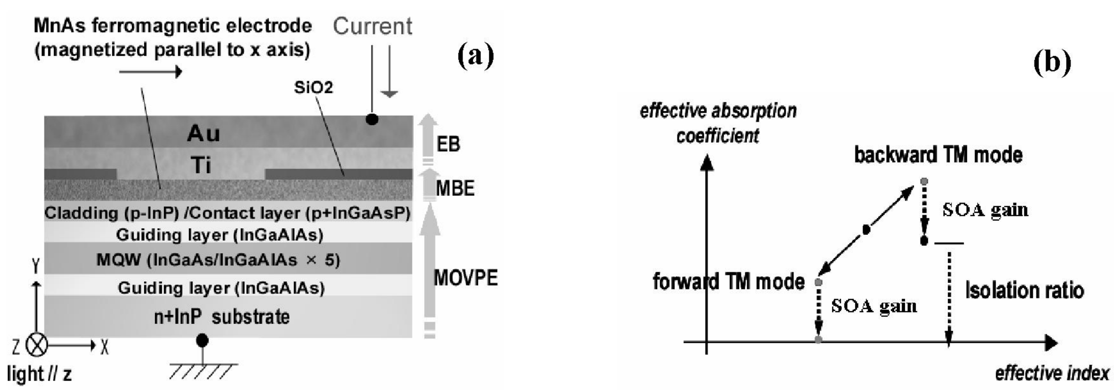

Fig. 1. (a) Schematic cross section of the TM-mode waveguide optical isolator. The MnAs layer is magnetizated along the *x* direction. Light passes through the device perpendicular to the figure (z direction). (b) Principle of the operation of the isolator based on the nonreciprocal loss shift.

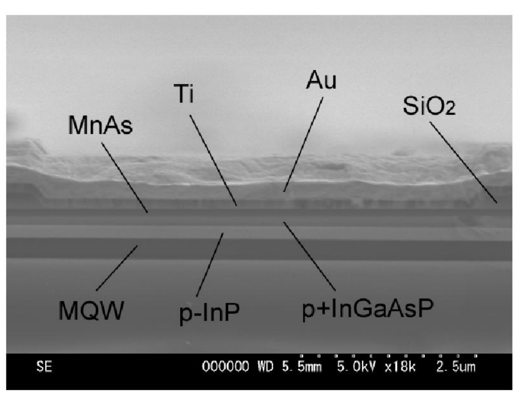

Fig. 2. Cross section of the TM-mode optical isolator observed with a scanning electron microscope (SEM).

3 Device operation

We measured light propagation in the device. Our experimental setup for measurement consisted of a wavelength-tunable laser with a polarization controller, optical circulators and switches, and an optical spectrum analyzer. A tunable laser generated light and sent it to the device through the polarization controller. The light was transferred into and out of the device by end-fire coupling. The device was 0.6 mm long and as cleaved. During measurement, the device was set at 15 °C, drived with a current of 100 mA, and magnetized with an external magnetic field of 0.1T.

Figure 3(a) shows the isolation characteristics for the TM mode. The intensity of light at the output end of the device is plotted as a function of the wavelength for forward and backward propagation. The wavelength of incident light was fixed to 1540 nm. The output intensity for the TM mode changed by 5.3 dB by switching the direction of light propagation. The device efficiently operated as a TM mode isolator and had an isolation ratio of 8.8 dB/mm (= 5.3 dB/0.6mm).

Figure 3(b) plots the output intensity and isolation ratio as a function of the wavelength for forward and backward propagation for the TM mode. The wavelength of light was changed from 1520 nm to 1560 nm. The output of the tunable laser was fixed to 5 dBm. A maximum isolation ratio was observed at 1540 nm——the wavelength at which the SOA exhibited a gain peak.

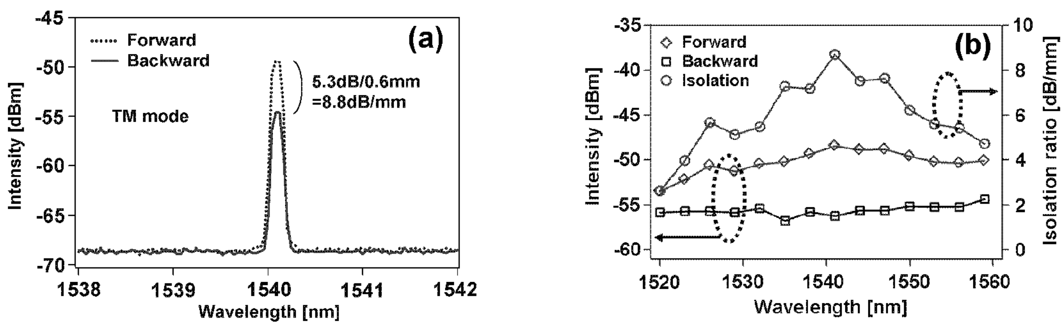

Fig. 3. (a) Nonreciprocal propagation in our waveguide isolator measured for the 1540 nm TM mode, and (b) wavelength dependence of the optical transmission and the isolation spectra. The waveguide isolator drived with a 100 mA current and magnetized with a 0.1 T external field.

4 Conclusions

We developed a prototype of 1540 nm, TM mode waveguide isolators. The device consists of an InGaAlAs/InP active waveguide with a ferromagnetic MnAs layer, making use of nonreciprocal loss shift. The MnAs layer serves a dual function of producing the nonreciprocal effect with its ferromagnetism and of making a low-resistive ohmic contact on the waveguide. The device had an isolation ratio of 8.8 dB/mm at a wavelength of 1540 nm. These results mean that we can proceed to polarization-insensitive waveguide isolators for photonic integrated circuits.

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