Single mode operation of 1.5 µm TM-mode waveguide optical isolators based on the nonreciprocal-loss phenomenon

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Abstract: We developed a 1.5-µm-band, TM-mode waveguide optical isolator consisting of a semiconductor ridge waveguide combined with a ferromagnetic MnAs layer. The device shows single mode operation with an isolation ratio of 7.2 dB/mm at 1.53-1.55 µm wavelength.

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

1 Developing waveguide optical isolators

Optical isolators are indispensable elements to photonic integrated circuits for interconnecting various optical devices without problems caused by undesirable reflection of light in the circuit. They are required to have the form of a semiconductor waveguide because they must be monolithically combined with other waveguide-based optical devices on a semiconductor substrate. One promising way of creating waveguide isolators is by making use of a magneto-optic phenomenon called the *nonreciprocal loss* where——in an magneto-optic waveguide——the absorption loss of light is larger in backward than in forward propagation [1, 2]. To construct 1.5-µm-band, polarization-independent waveguide isolators, we developed TE-mode devices based on this phenomenon and then began TM-mode devices [3, 4]. Our prototype TM-mode device, however, had a simple gain-guiding structure with a small lateral-confinement factor and therefore left room for improvement; that is, it was unable to operate in a single mode and showed a large forward loss. To solve these problems, we improved the device to have a ridge waveguide structure with a large lateral-confinement factor. We designed the improved structure with the aid of simulations using finite-difference method and then fabricated an actual device. The following sections provide the details on this improved TM-mode isolator.

2 Structure of the TM-mode waveguide isolator

Figure 1 shows a cross section of our ridge waveguide isolator. It consists of a TM-mode semiconductor optical amplifier (SOA) on an n-type InP substrate covered with a ferromagnetic manganese-arsenide (MnAs) layer. The SOA consists of an InGaAs/InGaAlAs multiple quantum well (MQW) sandwiched between two InGaAlAs guiding layers; the upper guiding layer is covered with a p-type InP cladding layer and a highly doped p-type InGaAs contact layer. An Au-Ti metal layer on the MnAs layer forms a top electrode to supply driving current to the SOA. Incident light passes through the SOA waveguide 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 denoted by the arrow in the figure (x direction). The magneto-optic transverse Kerr effect occurs in this structure and produces a difference in an effective extinction coefficient for TM-mode light between forward (z direction) and backward propagation ($-z$ direction). In consequence, the absorption loss is larger for backward than for forward propagation. The SOA compensates for the forward propagation loss; it is operated so that the net loss for forward propagation will be zero. 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 SOA waveguide. MnAs is superior for this purpose to ordinary ferromagnetic metals.

3 Fabricating the device

The substrate was a highly doped, [100]-oriented n-type wafer of InP. The SOA was grown using metal-organic vapor phase epitaxy (MOVPE); the MQW consists of InGaAs quantum wells (-0.4 % tensile-strained) and six InGaAlAs barriers (+0.6% compressive-strained). The thickness of each layer was: 100 nm for the InGaAlAs guiding layers, 350 nm for the InP cladding layer, and 10 nm for the InGaAs contact layer. On the contact layer, a 200-nm-thick MnAs layer was grown using molecular-beam epitaxy (MBE). To make the ridge waveguide structure, the MnAs layer was selectively removed using photolithography and inductively coupled plasma etching, and the cladding and the contact layers were selectively removed using wet etching. The width of the waveguide was set to 2 µm. On this ridge waveguide, a 100-nm Al_2O_3 layer was deposited using electron-beam evaporation (EB), and a window was opened by means of a lift-off process. After that, a 100-nm Ti layer and a 200-nm Au layer were deposited to make a top electrode. Finally, both ends of the device were cleaved; the cleaved surfaces were left uncoated. Figure 1(b) shows the cross section of the device observed with scanning electron microscopy (SEM). The MnAs layer on the contact layer showed strong magnetocrystalline anisotropy and was easily magnetized along the [011] direction of the InP substrates. Therefore, we formed the waveguide stripe parallel to the [0-11] direction of the InP substrate, and applied an external magnetic field to the [011] direction (x-direction in Fig. 1(a)).

4 Device operation

The device functioned successfully as an optical isolator. We sent light from a tunable laser to one end of the device and measured the output from the other end using an optical spectrum analyzer. The wavelength of incident light was fixed at 1.54 µm. During measurement, the device was set at 20 ^{o}C, driven with a current of 100 mA, and magnetized with an external magnetic field of 0.1 T. Figure 2(a) shows the result; the intensity of output light is plotted as a function of wavelength for forward and backward propagation. An isolation ratio of 7.2 dB/mm (= 4.7 dB/0.65 mm) was obtained. From 1.53 to 1.55 µm, the isolation ratio was almost constant. The photograph inset in Fig. 2(a) is the near-field pattern of the forward propagating light, showing that the device worked in a single mode.

The data of transmission intensity in Fig. 2(a) include the fiber coupling loss and the measurement system loss. To examine the intrinsic loss in the device, we measured the transmission intensity of devices with different values of length. Figure 2(b) shows the result, i.e, the output intensity for forward and backward transmission as a function of device length (isolation ratio is also plotted). The slope of the forward line gives the intrinsic absorption loss per unit length, and we estimated that forward loss in the 0.65-mm-long device was 6.9 dB——a far smaller loss than that in our previous device with gain-guiding structure (~ 30 dB/mm). To reduce the forward loss to 1 dB/mm or less, we are now developing improved devices with twice the number of MQW wells.

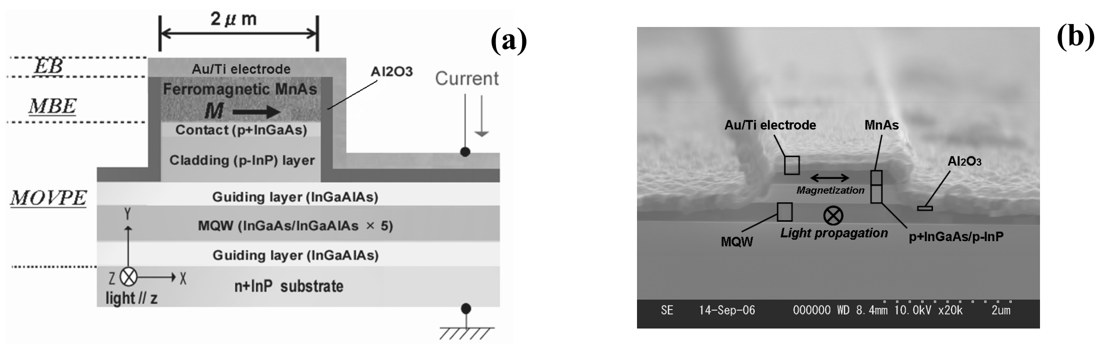

Fig. 1 (a) Schematic cross section of the TM-mode waveguide optical isolator. The MnAs layer is magnetizated along *x*-direction. Light passes perpendicular to the figure (z-direction). (b) Cross section of the device observed with a SEM.

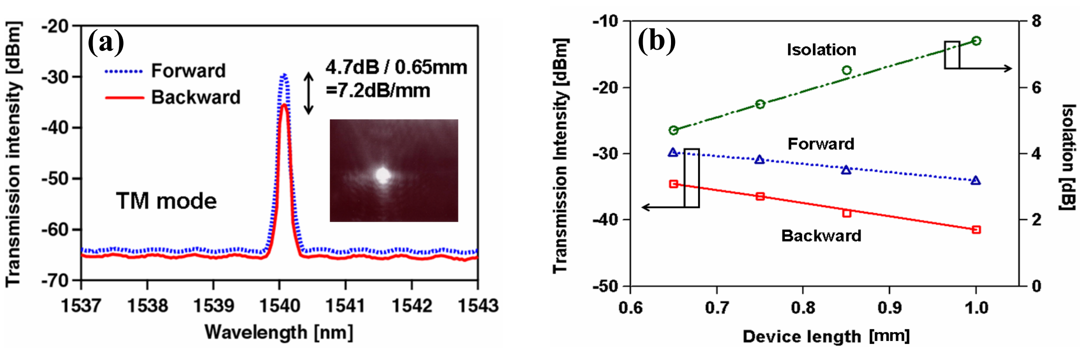

Fig. 2 (a) Forward and backward transmission through the device with 0.65-mm length, measured for 1.54 µm TM-mode light, with 100 mA driving current and 0.1 T magnetic field. (b) Transmission intensity and isolation ratio as a function of device length.

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