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Double-Dielectric-Loaded Plasmonic Optical Isolator for Integration into Photonic Integrated Circuits

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Abstract

A new structure of surface plasmons waveguides for an integrated optical isolator has been proposed. It is composed of a ferromagnetic metal covered with a low and high refractive index layers. This structure is supposed to have a good coupling efficiency with a dielectric waveguide and 30 dB isolation with less than 10 dB insertion loss in the device length of 300 µm.

1. Introduction

Optical isolators are essential devices for optical telecommunications in order to prevent back reflected light which causes noise in laser diodes. However, conventional isolators are not suitable for integration into photonic integrated circuits (PICs) due to their bulk components, such as a Faraday rotator and polarizers, and incompatibility between magneto-optical (MO) rare-earth iron garnets and semiconductors. In spite of many studies having done, monolithically integrated optical isolators are still in research stage. Furthermore, it is desirable that the device length is comparable with that of laser diodes.

To overcome this issue, we utilize nonreciprocal magneto-optical (MO) effect of ferromagnetic metal enhanced by surface plasmon polaritons (SPPs). It is possible to achieve a significant reduction of the optical loss and the enhancement of transverse-MO effect which yields nonreciprocal propagation loss for SPPs propagating between a double-dielectric and a ferromagnetic-metal interface [1, 2]. However, a coupling efficiency between a dielectric waveguide and a plasmonic waveguide is always problem for monolithic integration. In this paper, we show a plasmonic optical isolator using a dielectric-loaded surface plasmon polariton waveguide (DLSPPW).

2. Working Principle and Device Design

Isolation principle

SPPs can occur between a negative (typically, noble metal) and a positive permittivity substances. In the case of substituting a ferromagnetic metal for a noble metal and put on another dielectric which has higher refractive index (see Fig. 1), the SPPs would be partially drawn into the high-index dielectric. This state reduces the attenuation of the metal and makes the confinement of SPPs unstable. The permittivity of a ferromagnetic metal can be changed by the transverse-MO effect non-reciprocally; therefore, the propagation constant/loss of SPPs can be easily changed according to the propagation direction due to the unstable confinement. The optical field distribution is schematically depicted in Fig. 1. The forward and the backward propagating light are distributed away from (blue curve) and nearby (red curve) a lossy ferromagnetic metal, respectively.

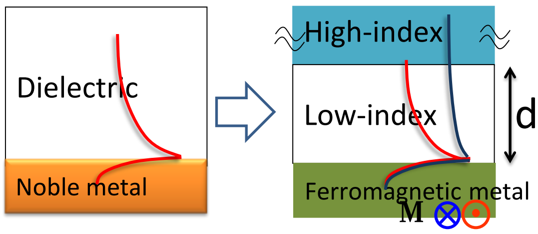

Fig. 1 An application of the SPPs to a plasmonic optical isolator with double-dielectric/ferromagnetic-metal structure.

Device design

A DLSPPW has been reported to have a small propagation loss and a high coupling efficiency of ~1 dB/transition with a dielectric waveguide [3, 4]. We modified this DLSPPW with the double-dielectric/ferromagnetic-metal configuration as shown in Fig. 2. Light propagates in a Si ridge-waveguide on SOI substrate and goes into Fe-SiO_2 DLSPPW covered with Al_2O_3. In this double-dielectric loaded plasmonic isolator, the SiO_2 works as a low-index (n=1.44) layer and confines SPPs with Fe. The Al_2O_3 works as a high-index layer (n=1.746) and makes the confinement of SPPs unstable. Transversely magnetized Fe gives nonreciprocal attenuation by the transverse-MO effect depending on the propagation direction.

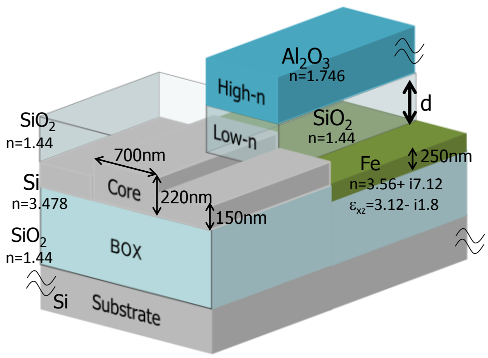

Fig. 2 The front side of the double-dielectric loaded plasmonic isolator coupled with a Si (SOI) waveguide.

3. Calculation of Optical Properties

We have calculated the influence of the high and the low index layers on the optical properties of SPPs. Figure 3 shows 1/e propagation distance and the isolation as a function of the film thickness of SiO_2 calculated by 1 dimensional effective index method (EIM) at the wavelength of 1.55 μm. If the SiO_2 thickness d is infinite, SPPs can be completely confined between Fe and SiO_2 with the high propagation loss. With reducing the thickness, the confinement becomes close to a cutoff condition (broken vertical line); therefore, the propagation distance rapidly increases improving both the isolation and the insertion loss. The isolation reaches ~0.1 dB/μm, and the insertion loss is less than ~0.04 dB/μm in the film thickness range of 535–542 nm. This enables 30 dB isolation with less than ~10 dB insertion loss in only ~300-μm device length.

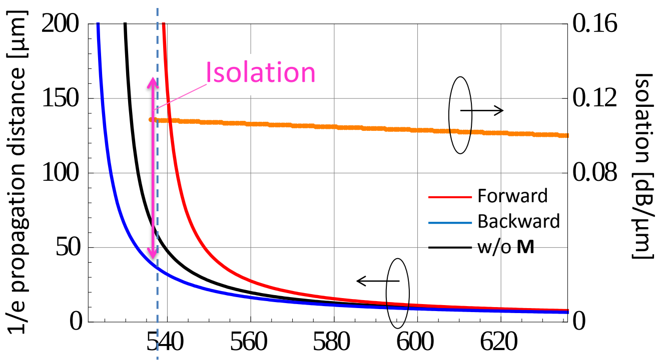

Fig. 3 1/e propagation distance and the isolation as a function of the SiO_2 film thickness d. The forward and the backward propagating light are indicated respectively by red and blue curves. The black curve shows the case of no magnetization.

Figure 4 shows the cross-sectional optical field profile of TM mode at the SiO_2 thickness of 536 nm by 2D EIM. It is found that the SPPs are excited on the dielectric-loaded Fe surface with weak confinement. A little larger leakage of light into the Al_2O_3 layer is observed in the left figure (forward propagation) than in the right figure (backward propagation) as indicated by the broken circle.

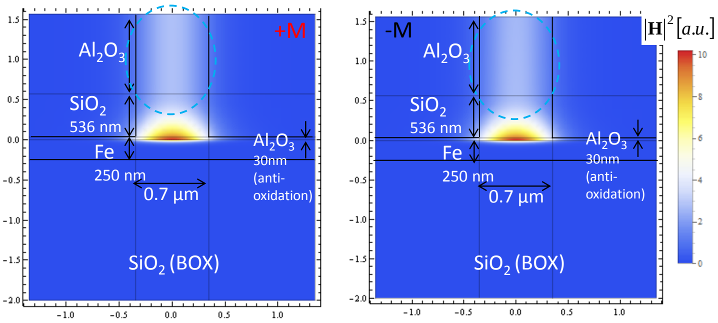

Fig. 4 Optical field profiles of TM mode with magnetization, +M (left) and –M (right), in the same structure.

We have simulated the coupling and the effect of the double-dielectric structure by 3D finite difference time domain (FDTD) method in Fig. 5. We assumed Fe-SiO_2 DLSPPW of 5-μm length between SOI waveguides with (right) and without (left) the top Al_2O_3 layer. It was shown that light was clearly coupled with the DLSPPW in the both cases. The propagation loss of plasmonic isolator was reduced by adding high-index Al_2O_3 layer (right) compared to that with air cladding layer (left). This is because the Al_2O_3 layer draws the propagating light and gets around the light absorption of Fe.

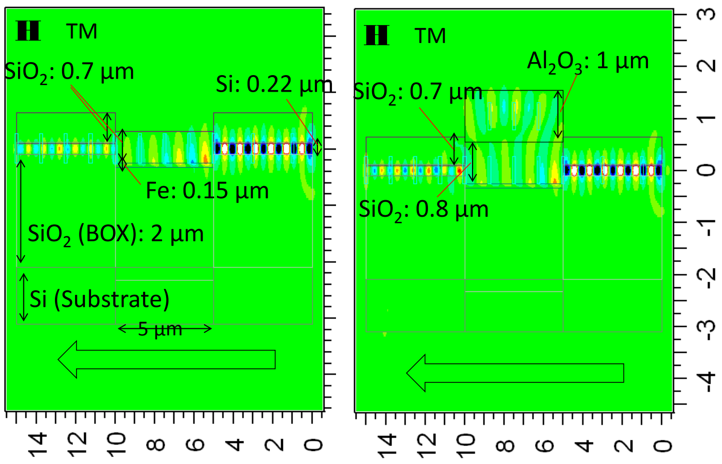

Fig. 5 FDTD simulation on the Fe-SiO_2 DLSPPW with (right) and without (left) the top Al_2O_3 layer coupled between SOI waveguides. TM-mode light at the wavelength of 1.55 μm is incident at the right facet.

4. Conclusions

An integrated optical isolator utilizing surface plasmons in a double-dielectric loaded ferromagnetic metal structure has been proposed. It was designed with the aim of high coupling efficiency and high isolation with low insertion loss. Calculations have shown 30 dB isolation with less than 10 dB insertion loss in the device length of 300 μm and a clear coupling with a dielectric waveguide.

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