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Technologies to reduce insertion loss of plasmonic isolator integrated with Si nanowire waveguides

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Abstract

The fabrication technology of a low-propagation-loss plasmonic waveguides were optimized. It was found that both the out-of-plane confinement and the in-plane confinement are critically important in order to obtain a low propagation loss of a surface plasmon. Long-distance propagation of a surface plasmon on the surface of a ferromagnetic metal was demonstrated. A low propagation loss of 0.7 dB/μm for a surface plasmon in a Co/TiO2/SiO2 plasmonic structure and a moderate coupling efficiency of 4 dB per facet between plasmonic and Si waveguide were achieved.

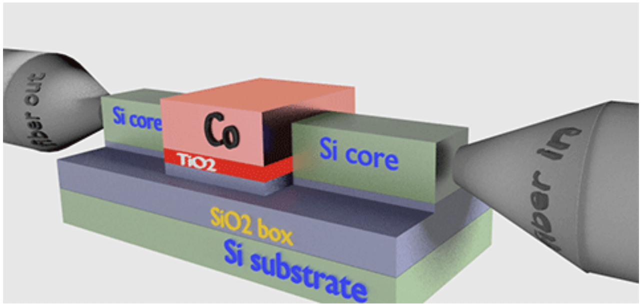

Fig.1 Integration of a $Co/TiO_2/SiO_2$ plasmonic waveguide with a Si nanowire waveguide.

1. Introduction

The optical isolator is an important element of optical networks. It protects optical elements from unwanted back reflection. The integration of optical elements into Photonic Integrated Circuits (PIC) is an important task, because it may reduce a cost and improve performance of high-speed optical data processing circuits for the high-speed optical networks. The optical isolator is one of a few optical components, which has not yet been integrated into commercial PIC. The integration of an optical isolator is important for PIC, because the problem of back-reflected light is more severe in the case of integrated optical elements. At present, there is a there is a commercial need for the integrated isolator [1-2].

A new design of an integrated optical isolator, which utilizes unique non-reciprocal properties of surface plasmons, has been proposed [3-4]. The merits of pasmonic isolator are a small size and a good compatibility of its fabrication technology the fabrication technology of the PIC [2-4].

2. Plasmonic isolator

Figure 1 shows a design of the plasmonic isolator. It consists of a nanowire waveguide, small part of which (about 2-16 μm) is etched out, and a ferromagnetic metal is deposited in the gap. The cobalt is not transparent and the light propagation from input waveguide to output waveguide is blocked by the Co. However, a surface plasmon is excited at Co-TiO2/SiO2 interface and light can reach from the input fiber to output fiber. The Co is magneto-optical material and its optical properties are non-reciprocal. It means that they are different for two opposite directions of light propagation. The plasmonic waveguide containing the Co is optimized so that a plasmon is excited in one direction, but a plasmon cannot be excited in the opposite direction. Therefore, light can pass from input to output only in forward direction, but light is blocked in the opposite direction.

A possible dense integration of optical components is main benefit of both the Si nanowire waveguides and the plasmonic waveguides. The integration of different optical components on one substrate has many benefits. Similar to electronic devices, an integrated optical circuit may have a lower cost and better functionality.

The propagation loss is unavoidable for a surface plasmon. In the data-processing devices a low insertion optical loss is a critical parameter and the surface plasmons with the smallest propagation loss should be used [1]. It is known [2] that the propagation loss of the surface plasmons in ferromagnetic metals like Fe, Co or Ni is at least an order of magnitude larger than the optical loss of plasmons in Au, Ag and Cu, which are the conventional metals for the plasmonic devices. The 1/e propagation distance of a surface plasmon in a ferromagnetic metal is shorter or about a micrometer [2]. The high propagation loss is the reason why a long-range surface plasmon has not been observed directly on a surface of a ferromagnetic metal. In this work we demonstrate the low propagation loss of 0.7 dB/μm in a plasmonic waveguide made of cobalt.

2. Out-plane confinement of a surface plasmon

A metal absorbs light. The less light is inside of the metal and the more light is inside of the dielectric, the smaller propagation loss is. For a simplest plasmonic structure, which consists of one dielectric covered by a metal, the ratio between amounts of light inside the dielectric and metal is fixed by the dielectric constants of metal and dielectric and it cannot be optimized. In contrast, in a double-dielectric or

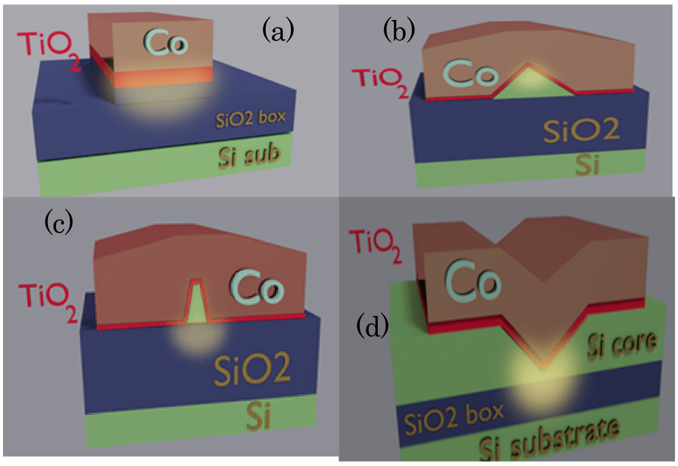

Fig.2 Lateral optical confinement of plasmons. (a) metal stripe; (b) wedge-type; (c) bridge-type; (d) grove-type. The distribution of optical field is shown in yellow color. The propagation direction of a plasmon is perpendicularly to the page. Top and bottom Si is shown in green color.

multi-dielectric plasmonic structure, the thickness of one dielectric can be optimized so that the amount of light in the metal becomes smaller and the amount of light in the dielectric becomes larger. It makes the smaller propagation loss of a surface plasmon [3-5].

Additionally to reduction of loss, the magneto-optical (MO) effect can be significantly enhanced in a plasmonic structure with a multilayer dielectric. This fact has been proved both theoretically [3,4,6,8] and experimentally [7]. About 100% of enhancement of the MO has already been demonstrated experimentally [7].

3. In-plane confinement of a surface plasmon

When out-plane confinement of a plasmonic waveguide is optimized, the optical loss due to the scattering of light at the edge of the metal becomes the major contributor to the optical loss of a plasmon.

Often a metal stripe is used for in-plane confinement of a plasmon (Fig.2 (a)). In this case a surface plasmon propagates just under the metallic stripe. There is a substantial amount of light at the metal edge and plasmon's propagation loss is high of about 8 dB/µm.

We have studied 3 types of efficient in-plane confinement for a surface plasmon: groove type, wedge-type and bridge-type. Measured plasmon propagation loss is 1.2, 1.0 and 0.7 dB/µm, respectively. All these types of the in-plane confinement are effective to reduce the propagation loss of a plasmon. The reason of the reduction of the propagation loss is that light is removed from the place of the metal edge.

3. Measurements of plasmon propagation loss and plasmonic-to-Si waveguide coupling efficiency

Figure 3 shows the fiber-to-fiber transmission as function of wavelength for different lengths of the Co/TiO2/SiO2 bridge-type plasmonic waveguide integrated with a Si nanowire waveguide (See Fig. 1). The black line

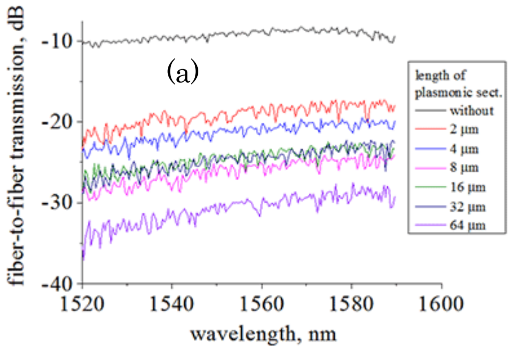

Fig.3 Fiber-to-fiber transmission as function of wavelength for different lengths of $Co/TiO_2/SiO_2$ bridge-type plasmonic waveguide integrated with Si nanowire waveguide.

shows the case of Si waveguide without plasmonic section. The 10 dB correspond to fiber-waveguide-fiber coupling loss. The red line shows the case of the shortest length of plasmonic section. In this case, the propagation loss can be ignored and the loss is only due to the coupling loss. From additional loss due to elongation of the plasmonic section, the plasmon' propagation loss is calculated. The propagation loss is 0.7 dB/µm and it is nearly independent on wavelength. The coupling loss between plasmonic and Si nanowire waveguides is 4 dB per a facet.

3. Conclusions

We have found that both the out-of-plane confinement and the in-plane confinement are critically important in order to obtain a low propagation loss of a surface plasmon. The out-of-plane confinement reduces the amount of light inside the metal. The in-plane confinement laterally confines the surface plasmon out of a metal edge.

We have fabricated a Co-based plasmonic waveguide with a low propagation loss of 0.7 dB/µm. at λ=1550 nm. We have monolithically integrated this plasmonic waveguide with a Si nanowire waveguide with a moderate coupling loss of 4 dB per a facet.

Acknowledgements

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