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Experimental demonstration of long-distance propagation of a surface plasmon on the surface of a ferromagnetic metal

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Abstract

A method for the reduction of the propagation loss of surface plasmons was proposed and experimentally demonstrated for plasmonic waveguides fabricated on both GaAs and Si substrates. Long-distance propagation of a surface plasmon on the surface of a ferromagnetic metal was demonstrated. A low propagation loss of 0.03 dB/μm for a surface plasmon in a Fe/SiO2/AlGaAs plasmonic structure on a GaAs substrate and a low propagation loss of 0.7 dB/μm for a surface plasmon in a Co/Ti2O3/SiO2 plasmonic structure on a Si substrate were achieved.

1. Introduction

A new design of an integrated optical isolator, which utilizes unique non-reciprocal properties of surface plasmons, has been proposed [1]. The main obstacle for a practical realization of the proposed design is a substantial propagation loss of the surface plasmons in structures containing a ferromagnetic metal. It is known [1-2] 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 reduction of the propagation loss of a surface plasmon is the key to make the plasmonic isolator competitive with other designs of the integrated isolator.

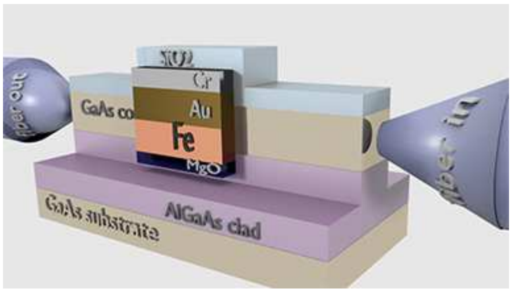

Fig. 1 Ferromagnetic plasmonic waveguide monolithically integrated with AlGaAs/GaAs optical waveguide. The transmission of light from input to output fiber is measured.

We have proposed [3] a new design of the plasmonic waveguide, which contains two dielectric layers. By optimizing this design, it is possible to reduce significantly the propagation loss and to increase the magneto-optical (MO) figure-of-merit. Using this method, the low propagation loss for a plasmon propagating on the surface of a ferromagnetic metal was achieved [4]. The propagation loss of 0.17 dB/μm for a surface plasmon in a Fe/MgO/AlGaAs plasmonic structure was experimentally demonstrated.

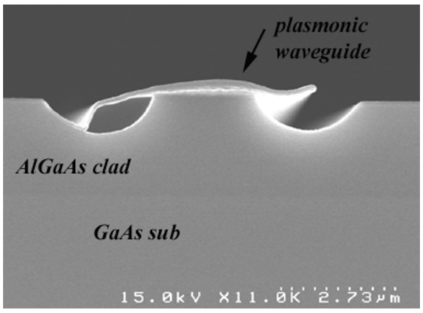

Fig. 2 SEM cross-sectional image of the under-etched plasmonic waveguide.

The optimized double-dielectric structure is efficient to reduce the light absorption by the metal. In the case of the plasmons with a low propagation loss, the other contributions to the plasmons loss may be essential. The light scattering at the side edges of metallic film may substantially contribute to the plasmon loss [4]. In order to reduce loss due to this contribution, we have proposed optimized plasmonic structures. We have demonstrated significant loss reduction for an under-etched plasmonic waveguide, which was fabricated on a GaAs substrate, and a wedge-type plasmonic waveguide, which was fabricated on a Si substrate.

2. Plasmonic waveguides on a GaAs substrate

Figure 1 shows the plasmonic waveguide monolithically integrated with an AlGaAs/GaAs optical waveguides. It consists of a stack of metallic layers embedded into an AlGaAs/GaAs optical waveguide. The metallic stack fully blocks the direct light propagation from the input waveguide to the output waveguide. Light can reach the output only when a surface plasmon is exited at the Fe/MgO surface. Because of the transverse non-reciprocal magneto-optical effect [4] in the iron, the propagation loss of the surface plasmons may be significantly different for the forward and backward propagation. In the case when in one direction the loss is small and in the opposite direction the loss is large, this simple structure operates as an optical isolator.

Figure 2 shows the cross-sectional Scanning-Electron Microscope Image (SEM) of the plasmonic waveguide. Under the metallic stack, the AlGaAs layer was partially wet etched. In this case there is almost no optical field of the plasmon near side edge of the metallic stack.

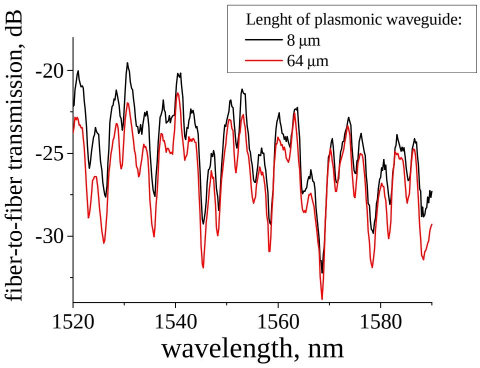

Fig. 3 Fiber-to-fiber transmission of the AlGaAs/MgO/Fe plasmonic structure embedded into the AlGAs/GaAs optical waveguide.

Figure 3 shows the measured fiber-to-fiber transmission for the propagation lengths of the surface plasmons of 8 μm and 64 μm. The difference in transmission was about 2 dB, which corresponds to the propagation loss of a surface plasmon of 0.03 dB/μm. The same value of the propagation loss was measured for plasmon-propagation lengths of 16 and 32 μm. The oscillations with the period of 3.3 nm and the amplitude of 7 dB are due to the multi reflections of a waveguide mode between waveguide interfaces with the fiber and with the plasmonic section. By fitting these oscillations, the coupling loss of 8.2 dB/facet between a waveguide mode and a surface plasmon is calculated. The coupling loss is larger than that of 2.2 dB/facet measured for the similar structure without the under etch [2].

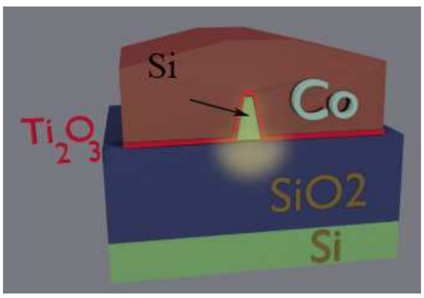

Fig. 4 Wedge-type Si/SiO2/Si/Ti2O3/Co plasmonic waveguide . The field distribution of plasmon is shown in yellow color.

3. Plasmonic waveguides on a Si substrate

The wedge-type $Si/SiO_2/Si/Ti_2O_3/Co$ plasmonic waveguides were monolithically integrated with a Si nanowire waveguides. The width and height of the Si nanowire waveguides were 450 and 220 nm, correspondingly. Because of smaller size, the edge scattering may be significant in the plasmonic waveguide. The wedge-type plasmonic waveguide is used in order to reduce this scattering loss.

Figure 4 shows the structure of the wedge-type $Si/SiO_2/Si/Ti_2O_3/Co$ plasmonic waveguides. The width and height of the Si wedge are 70 and 220 nm, correspondingly.

Figure 5 shows the fiber-to-fiber transmission, which is measured for different propagation lengths of the surface plasmons. There are no oscillations in the spectrum, because a spot-size converter was used. The spot-size converter significantly reduces the amount of back-reflected light at a fiber-waveguide facet. The plasmon's propagation loss was evaluated to be 0.7 dB/μm.

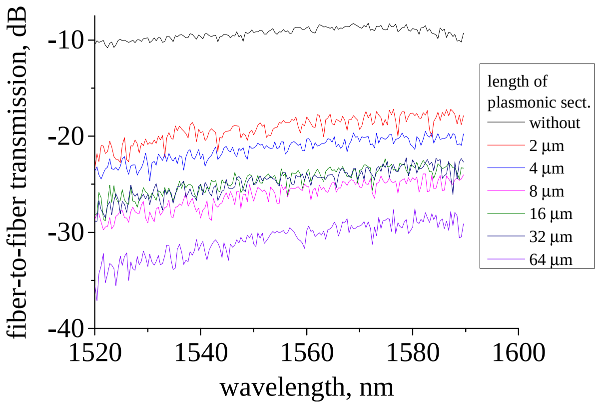

Fig. 5 Fiber-to-fiber transmission of the Si/SiO2/Si/Ti2O3/Co plasmonic waveguide integrated with a Si nanowire waveguides. The black line shows the transmission for a Si nanowire waveguide without a plasmonic section.

4. Conclusions

The optimized designs of the plasmonic waveguides were proposed and experimentally studied. The optimized double-dielectric structure, the under-etched structure and the wedge-type structure are effective to achieve a low-propagation loss in a plasmonic waveguide. A low propagation loss of plasmons was demonstrated for a ferromagnetic plasmonic structure integrated with AlGaAs optical waveguides on a GaAs substrate and integrated with a Si nanowire waveguides on a Si substrate.

References

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