

# Photonic Integration of Plasmonic Magneto-optical Waveguide and Si Nanowire (Invited)

Vadym Zayets, Hidekazu Saito, and Shinji Yuasa

Spintronics Research Center,

National Institute of Advanced Industrial Science and Technology (AIST),

Umezono 1-1-4, Tsukuba, Ibaraki 305-8568, Japan

E-mail: v.zayets@aist.go.jp

**Abstract**—A method for the reduction of the propagation loss of surface plasmons was proposed and experimentally demonstrated. Long-distance propagation of a surface plasmon on the surface of a ferromagnetic metal was demonstrated. A low propagation loss of 0.03 dB/ $\mu\text{m}$  for a surface plasmon in a Fe/SiO<sub>2</sub>/AlGaAs plasmonic structure on a GaAs substrate and a low propagation loss of 0.7 dB/ $\mu\text{m}$  for a surface plasmon in a Co/TiO<sub>2</sub>/SiO<sub>2</sub> plasmonic structure on a Si sub-strate were achieved

**Keywords**—surface plasmons, Si nanowire waveguides, optical isolator, photonic integrated circuits

## I. 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 the 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 commercial need for the integrated isolator [6–10].

A new design of an integrated optical isolator, which utilizes unique non-reciprocal properties of surface plasmons, has been proposed [1]. The merits of plasmonic isolator are a

small size and a good compatibility of its fabrication technology with the fabrication technology of the PIC [1].

Figure 1 shows a design of the plasmonic isolator. It consists of a nanowire waveguide, small part of which (about 2-16  $\mu\text{m}$ ) 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-TiO<sub>2</sub>/SiO<sub>2</sub> 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 can not be excited in opposite direction. Therefore, light can pass from input to output only in forward direction, but light is blocked in the opposite direction. A device, which is transparent only in one direction, is called the optical isolator. Figure 2 shows a top view of a Co/TiO<sub>2</sub>/SiO<sub>2</sub> plasmonic waveguides of different lengths integrated with a Si nanowire waveguides.

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. In the case of an electronic circuit, the size of MOSFET transistors are very small and millions of the transistors can be integrated into one electrical circuit. Because

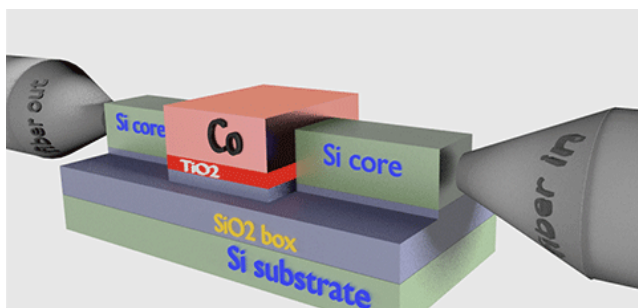


Fig.1 Integration of a Co/TiO<sub>2</sub>/SiO<sub>2</sub> plasmonic waveguide with a Si nanowire waveguide. From input fiber (at right), light is coupled into a Si nanowire waveguide (green) and into a plasmonic waveguide. Next, light is coupled again in a Si nanowire waveguide and finally into the output fiber (at left). Magnetization of Co is in-plane and it is perpendicular to light propagation direction

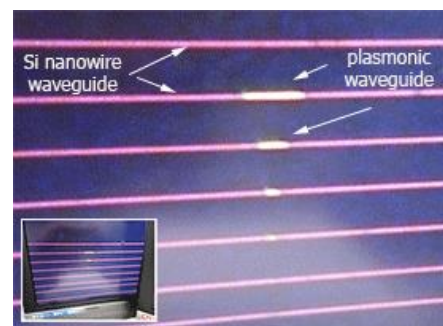


Fig.2 Top view from an optical microscope of Si nanowire waveguide integrated with plasmonic waveguides. Different lengths of the plasmonic waveguides is used in order to measure the optical loss. In the 2d from top waveguide the length of the plasmonic section is 64  $\mu\text{m}$ . The width of Si nanowire waveguides is 450 nm.

of the dense integration, the integrated electronic devices have a complex functionality and a low cost. It could be expected that similar to electronic dense-integrated circuits, an optical dense-integrated circuit may have a lower cost and better functionality. However, there is a problem for a dense integration of optical components. The problem is the size of optical component. The size of MOSFET transistors is very small and millions of the transistors can be integrated into one electrical circuit. In contrast, the size of optical components is not as small. The typical length of optical components is about a millimeter and only a few optical components can be integrated into one chip. The length of optical components is limited by the wavelength of light.

It is possible to reduce substantially the size of optical components when optical waveguides with a strong optical confinement such as a Si nanowire waveguide or a plasmonic waveguide.

The optical confinement in a Si nanowire waveguide is strong, because of a high refractive index contrast between Si and SiO<sub>2</sub>. Due to strong optical confinement, the Si nanowire waveguides are very narrow with width of 450 nm and they can sharply bend with bending radius as small as 1 mm. Even though the length of Si-nanowire devices has to be still relatively long, by bending the optical device can be packed into small area of a few μm<sup>2</sup>.

The refractive index is negative and the refractive index contrast in a plasmonic waveguide is very high. Optical confinement in a plasmonic waveguide is even stronger than in a Si nanowire waveguide and the size of optical components made of a plasmonic waveguide is even much smaller than size of elements made of Si nanowire waveguides. Plasmonic components are well fit for a dense optical integration.

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 [1–4]. The reduction of the propagation loss is the key parameter in order to fabricate a

competitive plasmonic device.

Moreover, for a plasmonic isolator a ferromagnetic metal has to be used in order to achieve the non-reciprocal function. It is known [13–15] 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 only a few of micrometers [14]. The high propagation loss is the reason why the long-range surface plasmons have not been observed directly on a surface of a ferromagnetic metal.

We have established the fabrication technology of a low-propagation-loss plasmonic waveguides. We have than an optimized in-plane and out-confinements of plasmons are critically important to obtain a low propagation loss of a surface plasmon. Using this method it is possible to achieve a long propagation of a plasmon on surface of different metals. We have experimentally demonstrated a long propagation of a surface of the cobalt.

## II. CRITICAL REQUIREMENTS FOR A PLASMONIC WAVEGUIDE

Any possible application of plasmonic waveguides in the Photonic Integrated Circuits could be practical only in when optical loss of the plasmonic section is low and it does not exceed 1-2 dB. This requirement is difficult, but possible to satisfy for a plasmonic waveguide. We have found that two conditions are critically important in order to fabricate a low-optical loss plasmonic waveguide. The first condition is the optimized out-plane confinement. The second condition is the optimized in-plane confinement.

A metal is essential material of a plasmonic waveguide. Any metal significantly absorbs light. Therefore, some optical loss is unavoidable in a plasmonic waveguide. In case if this loss is too large, all light is absorbed in plasmonic waveguide. Even if such plasmonic waveguide might have a unique property, it has no any practical use. Therefore, any practical plasmonic waveguide should have a reasonably-low propagation loss.

In the photonic integrated circuits the input and output of a plasmonic element are Si nanowire waveguides. The distributions of the optical field in a Si nanowire waveguide and a plasmonic waveguide are very different. As result, the coupling between optical and plasmonic waveguides could be weak. It causes a large coupling loss. By optimizing the out-plane and in-plane confinements, it is possible to reduce significantly the coupling loss.

As was mentioned above, without the optimized out-plane and in-plane confinements, the reasonably-long propagation of plasmons can be observed only in a few metals like gold and silver. In a non-optimized structure with a ferromagnetic metal, the plasmon' propagation distance is very short about 100 nm. For a long time it was considered that a ferromagnetic metal cannot support a surface plasmon. However, when both the out-plane confinement and the in-plane confinement of plasmons is optimized, the long propagation of plasmon in a ferromagnetic metal is achieved (See Fig.3).

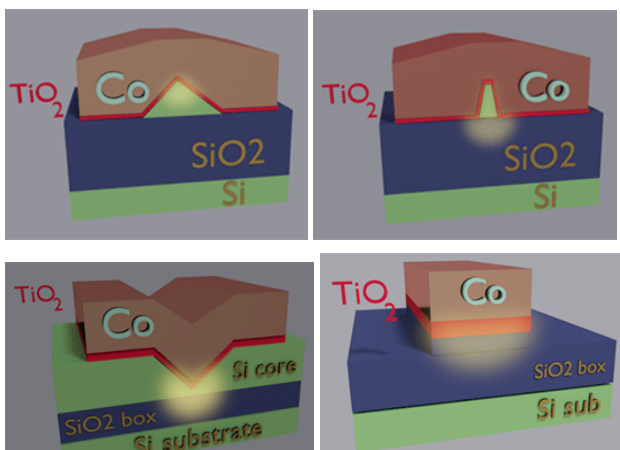


Fig.3 Lateral optical confinement of plasmons. (a) wedge-type (b) bridge-type; (c) groove-type; (d) metal stripe. The distribution of optical field is shown in yellow color. The propagation direction of a plasmon is perpendicularly to the page. Top and bottom Si is shown in green color.

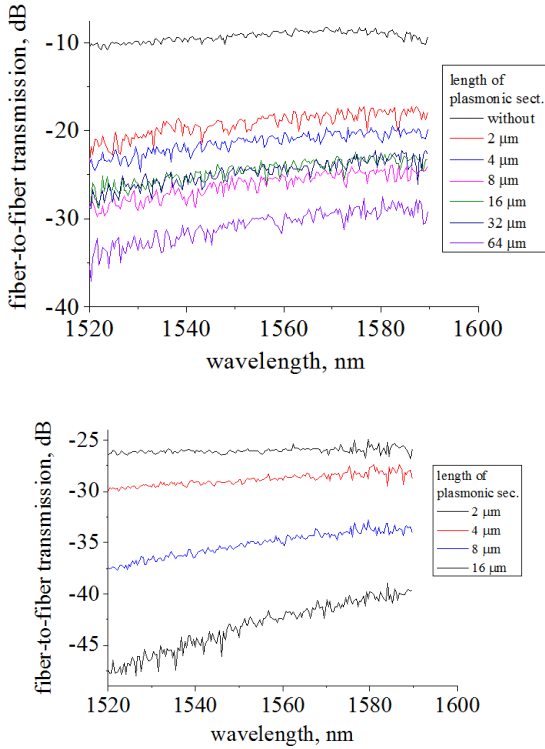


Fig.4 Fiber-to-fiber transmission as function of wavelength for different lengths of Co/TiO<sub>2</sub>/SiO<sub>2</sub> plasmonic waveguide integrated with Si nanowire waveguide. Type of lateral optical confinement of plasmons: (a) bridge-type; (b) wedge-type. The fiber-to-fiber transmission includes: (1) fiber-to-optical waveguide coupling loss is 5 dB per facet (2) plasmon-to-optical waveguide coupling loss is ~4 dB per facet (3) plasmon propagation loss ~ 1 dB/ $\mu$ m.

### III. 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 field distribution of a surface plasmon is known, the ratio between amounts of light inside the dielectric and metal is fixed by the dielectric constants of metal and dielectric and it can not be optimized. In contrast, in a double-dielectric or 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 [].

The reduction of optical loss in a plasmonic structure with an optimized multilayer dielectric is very effective. Often the optical loss in a plasmonic structure with an optimized multilayer dielectric is 10 or even 100 times smaller than in similar plasmonic structure with a single dielectric [].

Additionally to reduction of loss, the magneto-optical effect can be significantly enhanced in a plasmonic structure with a multilayer dielectric. This fact has been proved both theoretically [] and experimentally [].

### IV. 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 waveguide becomes the major contributor to the optical loss of a plasmon. The smoothness of waveguide edge is a critical parameter even for an optical waveguide. For example, in case of a Si nanowire waveguide a low optical loss can be obtained only in the case when roughness of edge of the waveguide does not exceed a few of nanometers. Such tough requirement is due to a large refractive index step between SiO<sub>2</sub> ( $n=1.44$ ) and Si ( $n=3.47$ ).

A metal has a negative refractive index and a refractive index step for a plasmonic waveguide is significantly larger. Therefore, the requirement for the smoothness of edge of a plasmonic waveguide is even tougher.

Often a metal stripe is used for in-plane confinement of a plasmon (Fig.3 (d)). In this case a surface plasmon propagates just under the metallic stripe. Even though the fabrication a stripe-type plasmonic waveguide is very simple, the propagation loss of a plasmon in such structure is very high. It is because technologically it is rather difficult to fabricate the edge of a metallic stripe with required smoothness. When it is possible, the stripe confinement of Fig.3(d) should be avoided in order to obtain a low propagation loss of a plasmon.

We have studied 3 types of in-plane confinement for a surface plasmon: wedge-type, bridge-type and groove type. All these types of the in-plane confinement are effective to reduce the propagation loss of a plasmon. The reason of the reduction is that light is removed from the place of the metal edge. In Fig.3 the calculated distribution of optical field of a plasmon is shown in yellow color. Only in case of the stripe-confinement,

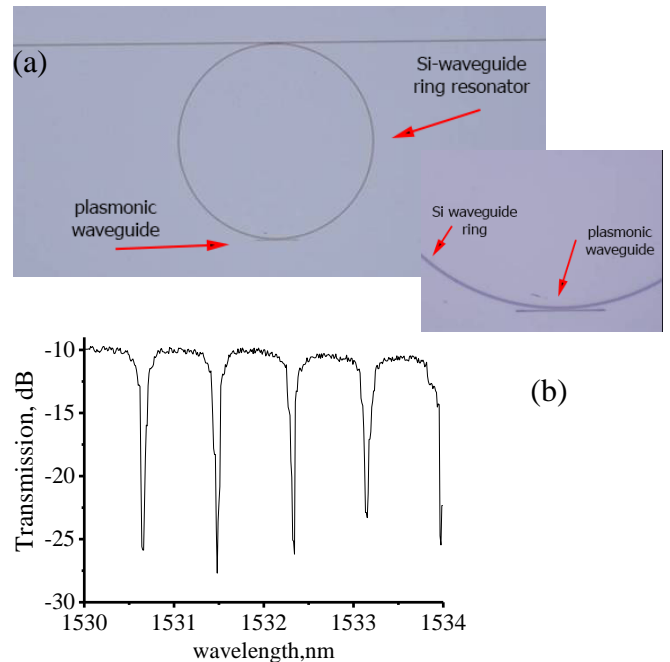


Fig.5. Plasmonic isolator of ring-resonator type. (a) Top view. The ring resonator is made of a Si nanowire waveguide. At the bottom there is a plasmonic waveguide, which is coupled to the ring. (b) Transmission of the ring resonator, when the gap between the ring and plasmonic waveguide is 600 nm.

the optical field is substantial at the edge of the metal. In other cases, there is practically no any optical field at the edge of the metal. Therefore, there is no light scattering at the edge.

All 3 types of in-plane confinement are well compatible with the fabrication technology of the Si nanowire waveguides and plasmonic waveguides. The top Si layer is used for the in-plane confinement. It is fabricated during the fabrication of the Si nanowire waveguides. For fabrication of a groove-type plasmonic waveguide, a Si stripe of width of 300 nm is remained unetched in the plasmonic section. Next, this stripe is wet etched to make it wedge-shaped. For fabrication of the bridge-type, a Si stripe of width of 70 nm is remained unetched in the plasmonic section. There is no any following wet etching. For fabrication of a groove-type plasmonic waveguide, a wide Si stripe of width of 1  $\mu\text{m}$  is remained unetched in the plasmonic section. Next, a  $\text{SiO}_2$  with a 200-nm-wide gap is fabricated on top of it. The groove was wet etched through the gap in the  $\text{SiO}_2$ .

The fabrication technology of a plasmonic waveguide of the bridge-type is simplest. It also gives plasmonic waveguides with a smallest propagation loss and a smallest coupling loss. Figure 4 shows the fiber-to-fiber transmission as function of wavelength for different lengths of Co/TiO<sub>2</sub>/SiO<sub>2</sub> plasmonic waveguide integrated with a Si nanowire waveguide (See Fig. 1). In case of a bridge-type plasmonic waveguide (Fig. 4(a)) the propagation loss is 0.7 dB/ $\mu\text{m}$  and it is nearly independent on wavelength. The coupling loss between plasmonic and Si nanowire waveguides is 4 dB per a facet. In case of a wedge-type plasmonic waveguide (Fig. 4(b)) the measured propagation loss is 1 dB/ $\mu\text{m}$  at  $\lambda=1.59 \mu\text{m}$  and 1.5 dB/ $\mu\text{m}$  at  $\lambda=1.55 \mu\text{m}$ . The reason of the substantial wavelength dependence of the plasmon' propagation loss is the wavelength dependence of the out-plane confinement for the wedge type plasmonic waveguides [1]. The measured coupling loss between plasmonic and Si nanowire waveguides is 6 dB per a facet.

The measurements of the fiber-to-fiber transmission of waveguides with different lengths of the plasmonic section (See Fig.2) allow measuring separately each contribution to the optical loss. The measurement of a waveguide without plasmonic section (black line of Fig.4(a)) gives the coupling loss between the fiber and the Si nanowire waveguide, which is 5 dB/facet in our case. The measurement of a waveguide with a short plasmonic section (red line of Fig.4(a)) gives the coupling loss between the plasmonic and Si nanowire waveguides. The measurement of longer waveguides gives the propagation loss.

## V. SERIAL VS PARALLEL INTEGRATION

As can be seen from Fig.4, the propagation loss of a plasmon is sufficiently small to fit the requirements for a plasmonic isolator and it could be even further reduced. However, the coupling loss between plasmonic and Si nanowire waveguides is still unacceptably high. The total insertion loss of realistic integrated device should be at least smaller than 1 dB. At present, the smallest coupling loss, which we have achieved, is about 4 dB per a facet. It means 8 dB per a device. By additional optimization, it might be possible to reduce twice the coupling loss. Further reduction might be

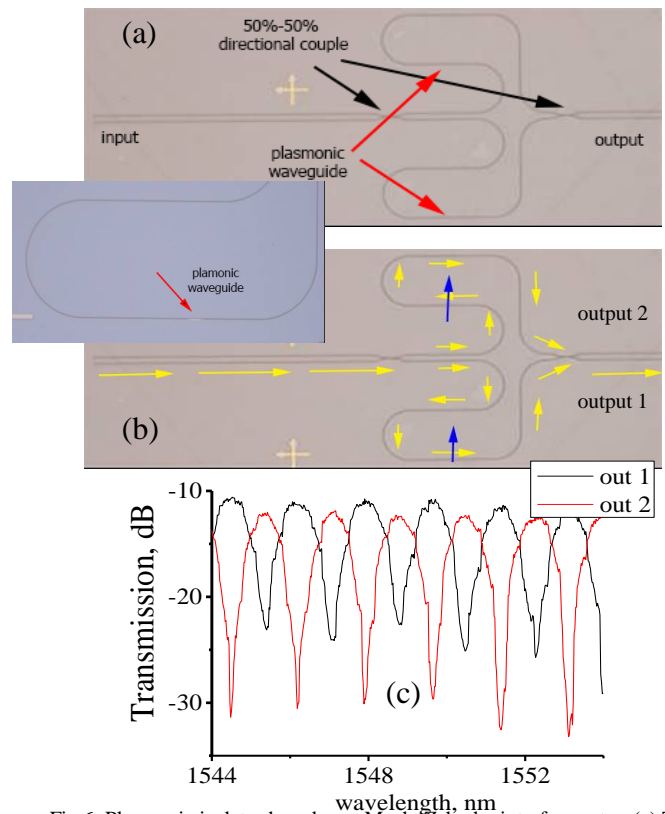


Fig.6. Plasmonic isolator based on a Mach-Zehnder interferometer. (a) Top view. The interferometer is made of a Si nanowire waveguide. At the bottom of each arm there is a plasmonic waveguide, which is coupled to the interferometer arm. (b) Yellow arrows show light propagation direction. Blue arrows show the magnetization direction of plasmonic waveguide. (c) Transmission of the asymmetric interferometer vs wavelength. The gap between the ring and plasmonic waveguide is 600 nm. Length difference of arms is 200  $\mu\text{m}$ .

difficult due to a substantial difference in field distributions of a plasmon and a waveguide mode.

One possible solution is the use of the parallel integration of plasmonic and Si nanowire waveguides instead the serial integration. Instead of the blocking of optical waveguide by plasmonic waveguide (See Fig.1), the plasmonic waveguide can be fabricated at a side of the optical waveguide (See Figs.5-7). In the later case, light is not blocked in the optical waveguide, but only it is only coupled in and out of the plasmonic waveguide. Therefore, in this case the difference of filed distributions between a surface plasmon and a waveguide mode is not issue and the insertion loss due to the plasmonic section cab be substantially reduced.

In the following, we describe 3 types of plasmonic isolator, where the parallel integration a plasmonic and a Si nanowire waveguides is used.

## VI. PLASMONIC ISOLATOR OF RING-RASONATOR TYPE

Figure 5(a) shows the fabricated plasmonic isolator of the ring-resonator type. The ring resonator is made of a Si nanowire waveguide. At the bottom of the ring there is a plasmonic waveguide. The gap between the ring and the plasmonic waveguide is narrow. It is between 50 nm and 600 nm. Light is coupled between the ring and plasmonic

waveguide. Figure 5(b) shows the measured of the fabricated device. There are narrow peaks, which correspond to the resonance frequency of the ring resonator. Because of non-reciprocal optical properties of the plasmonic waveguide, the positions of the resonance peaks are slightly different for opposite directions of light propagation. When wavelength of light is in the vicinity of a resonance peak, the transmission is different for opposite directions of light propagation and the device functions as an optical isolator. The demerit of this design is a narrow wavelength operation range.

### VII. PLASMONIC ISOLATOR BASED ON MACH-ZEHNDER INTERFEROMETER

Figure 6(a) shows the fabricated plasmonic isolator based on a Mach-Zehnder interferometer. The Mach-Zehnder interferometer is made of a Si nanowire waveguide. The input light is split into two arms of the interferometer by a 50% directional coupler and light is combined by the second 50% directional coupler. When there is no phase between two arms of the interferometer, the light is coupled into the first output port. When the phase difference is 180 degrees, the light is coupled into the second output port.

There is a plasmonic waveguide coupled into each arm of the interferometer. The gap between the interferometer arm and the plasmonic waveguide is narrow. It is between 50 nm and 600 nm. For the upper and lower arm the position of the plasmonic waveguide is different. The blue arrows of Fig. 6 (b) show the positions and the magnetization directions of the plasmonic waveguides. The yellow arrows show the direction of light propagation. Even though, two plasmonic waveguides magnetized in the same direction, their magnetization directions are different in respect to the light propagation direction. For the upper arm, the magnetization is toward the right hand. For the lower arm, the magnetization is toward the

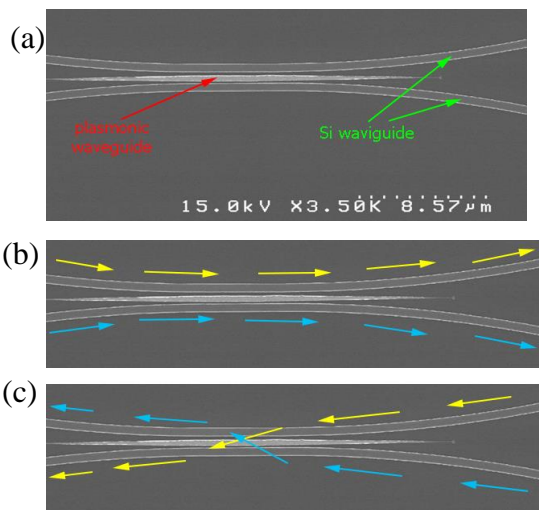


Fig.7. plasmonic isolator based on a non-reciprocal coupler (a) top view. There is a plasmonic waveguide between two Si nanowire waveguides; (b) Light path in forward direction; (c) Light path in backward direction. Yellow arrows show light coupled into input 1. Blue arrows show light coupled into input 2

left hand. Therefore, light experience the opposite magneto-optical effect in two arms of the interferometer. For the plasmonic isolator, the length of the plasmonic section is adjusted so that in the forward direction there is no phase between two arms of the interferometer and light passes through. In the opposite direction the phase difference is 180 degrees and light is blocked.

### VIII. PLASMONIC ISOLATOR BASED ON NON-RECIPROCAL COUPLER

Figure 7(a) shows the fabricated plasmonic isolator based on a non-reciprocal coupler. It consists of two coupled Si nanowire waveguides and a plasmonic waveguide between them. The width of the Si nanowire waveguide is 450 nm. The width of the plasmonic waveguide is 300 nm. The gap is 100 nm at both sides of the plasmonic waveguide. Light is coupled from one Si nanowire waveguide into plasmonic waveguide. Next, depending on the coupling parameters light either is coupled back into the same Si nanowire waveguide or it is coupled into another Si nanowire waveguide. Because of the non-reciprocal properties of the plasmonic waveguide, the coupling between two Si nanowire waveguide is different for two opposite light propagation directions. The coupler can be adjusted so that in forward direction the passes through the same Si waveguide (Fig. 7(b)), but in the backward direction the light fully coupled from one Si waveguide to another. Therefore, the coupler functions as an optical isolator.

### IX. FABRICATION TECHNIQUE: LIFT-OFF VS ARGON-ION MILLING

For fabrication of the plasmonic waveguides of Fig.2, the lift-off technique was used. The lift-off technique is convenient for the fabrication of plasmonic waveguides, because a metal is deposited only in the plasmonic section and other parts of the integrated photonic circuit are protected by an EB or photo resist from the deposition of a metal. The demerit of the lift-off technique is insufficient smoothness of the metal edge. As was explained above, the light scattering at a rough metal edge induces a huge propagation loss of a surface plasmon. An efficient in-plane confinement (Fig.3) has to be used in order to confine the plasmon out of the metal edge. It is a very efficient method to achieve a low propagation loss of a plasmon (See Fig.4). However, the method works well only for the case of the serial integration of the plasmonic waveguides (Figs 1 and 2). For the parallel integrations (Figs.5-7), light is coupled between a plasmonic and a Si nanowire waveguides at sides of the waveguides, where there is a metal edge. Therefore, in this case plasmon can not be confined out of the metal edge and there is a scattering at the edge.

In order to reduce the scattering and the plasmon' propagation loss, a smoother metal edge should be fabricated. It is possible to do using the Ar-ion milling technique. The Ar-ion milling gives a substantially-smoother metal edge, which has a weaker scattering. A demerit of the Ar-ion milling technique is that it requires the deposition on whole area of the PIC. Often it is hard to remove fully the metal from all different parts of the PIC. A feasible solution is a combination of the Ar-ion milling and the lift-off techniques.

## X. CONCLUSION

We have established the fabrication technology of a low-propagation-loss plasmonic waveguide and the technology of the integration of a plasmonic and Si nanowire waveguides. A possible dense optical integration is major merit of this technology.

We have that both the out-of-plane confinement and the in-plane confinement is 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.

Using this fabrication technique the different metals of different unique properties could be used in the plasmonic, additionally to traditionally-used gold and silver.

We have fabricated Co-based plasmonic waveguide with a low propagation loss of 0.7 dB/ $\mu\text{m}$ . at  $\lambda=1550$  nm. We have monolithically integrated this plasmonic waveguide with a Si nanowire waveguide with a moderate coupling loss of 4 dB per a facet.

In conventional plasmonic structure, the propagation loss of a plasmon on a surface of a ferromagnetic metal is very high and a ferromagnetic metal has never been considered as a metal for the plasmonic. The demonstration of a low propagation loss of a plasmon on surface of cobalt is a clear evidence for a high efficiency of the developed technology for fabrication of the plasmonic waveguides with a low plasmon' propagation loss.

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