Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

Report on plasmonic waveguide couplers

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Executive Summary

In this deliverable, we discuss our work done in developing efficient and broadband photonic-to-plasmonic mode converters. First, we introduce the working principle of the metallic tapered mode converter, discuss its fabrication and preliminary characterization results. We experimentally show that metallic taper mode converters provide very efficient means to convert the fundamental mode of a silicon nanowire waveguide to the gap surface plasmon polariton of a metallic slot waveguide with the conversion loss of less than 1dB.

In the second part of the deliverable, we report on a novel photonic to plasmonic mode converter for silicon photonics. The approach provides more than 85 % of conversion efficiency for a gap SPP of a horizontal metallic slot waveguide with a sub-50nm slot filled with various insulator materials. The proposed mode converter does not exhibit any resonant behaviour and can be operated in a wide wavelength range. It requires simple “bottom-up” fabrication approach and shows a good tolerance to fabrication errors.

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Background

Plasmonic phase modulator comprises two metal electrodes separated by a nanometer scale slot which is filled with an electro-optic polymer. Cross section of the device is given in Figure 1. At the 1550 nm wavelength, such plasmonic slot waveguide sustains gap surface plasmon polariton (SPP) mode which is strongly confined in the slot as can be seen in Figure 1. By applying a voltage between the metal electrodes, the refractive index of the electro-optic polymer can be modulated, which consequently results in modulation of SPP phase. One of the challenges in designing a modulator like this is to find an efficient way to excite the gap SPP in the structure. Within NAVOLCHI we have studied two configurations of mode converters, namely metallic taper based and multimode interference (MMI) based mode converters.

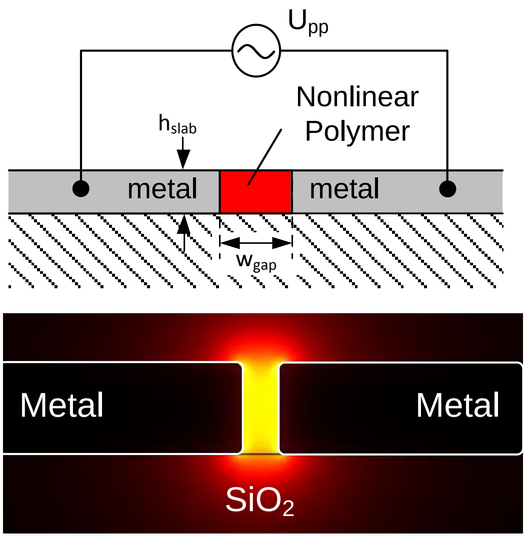

Figure 1 Cross section of the plasmonic phase modulator

In this deliverable, we introduce the two mode converter schemes. We describe the methods that have been used for optimizing the converters performances, find the geometrical and material properties that lead in maximum power transmission from silicon nanowire photonic mode to the gap SPP.

1. Metallic taper mode convert

A promising approach to couple light from a silicon nanowire to a plasmonic slot waveguide, we found to be the tapered metallic coupling configuration which provides very large and broadband coupling efficiency [1]. In such a coupling scheme, quasi-TE polarized light guided through silicon nanowire is adiabatically squeezed and launched into the plasmonic slot waveguide, see Figure 2. The parameters that influence the overall converter performance are tapering angle θ of the silicon nanowire and the distance *d* between the tip of the silicon waveguide and the metallic slot.

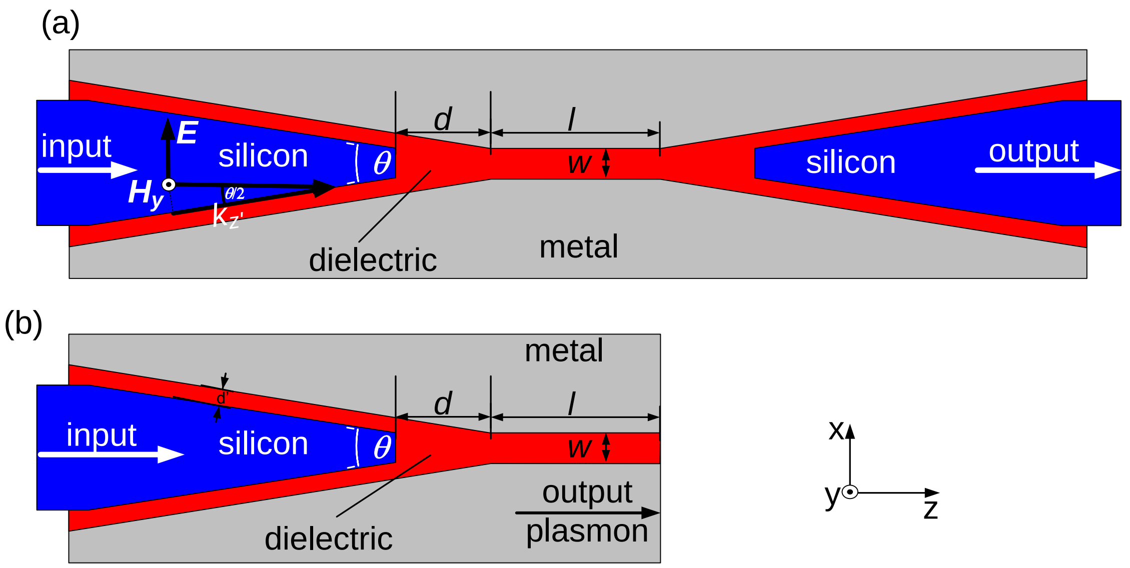

Figure 2 Geometry of plasmonic coupler, (a) top view of the realistic plasmonic modulator with two coupling sections and (b) structure used in optimization

The coupler is optimized for its highest transmission for the given silicon width of 500nm, dielectric material with a refractive index of 1.6. The realistic plasmonic modulator consists of two coupling sections for in- and out-coupling of the active region with a length of *l* as it is depicted in Figure 2(a). However, because of the limitation of the computational power, we have restricted ourselves in optimizing a single coupling section as the structure is symmetric relative to the central active section.

1.1 Simulation results

To calculate the SPP excitation efficiency we have performed simulation of the propagation of electromagnetic wave based on the Finite Integration Technique (FIT - CST Microwave Studio). To avoid from additional complexities in the computational, first the simulations have be carried out for 2D structure i.e. no refractive index variation along *y*-axis. The excitation efficiency of SPP in the metal-dielectric-metal structure is calculated as normalized transmission coefficient from the silicon waveguide to the plasmonic waveguide

$$transmission = \frac{P_{out}}{P_{in}} \tag{0.1}$$

where the P_{in} is the power at the input of the silicon waveguide and P_{out} the power at the output of the plasmonic waveguide, see Figure 2. The *transmission* is calculated varying the angle of the silicon tip θ, separation of plasmonic and silicon waveguides d. This is done for various plasmonic slot widths and dielectric refractive indices. The results of the refractive index of 1.6 are summarized given in Figure 3.

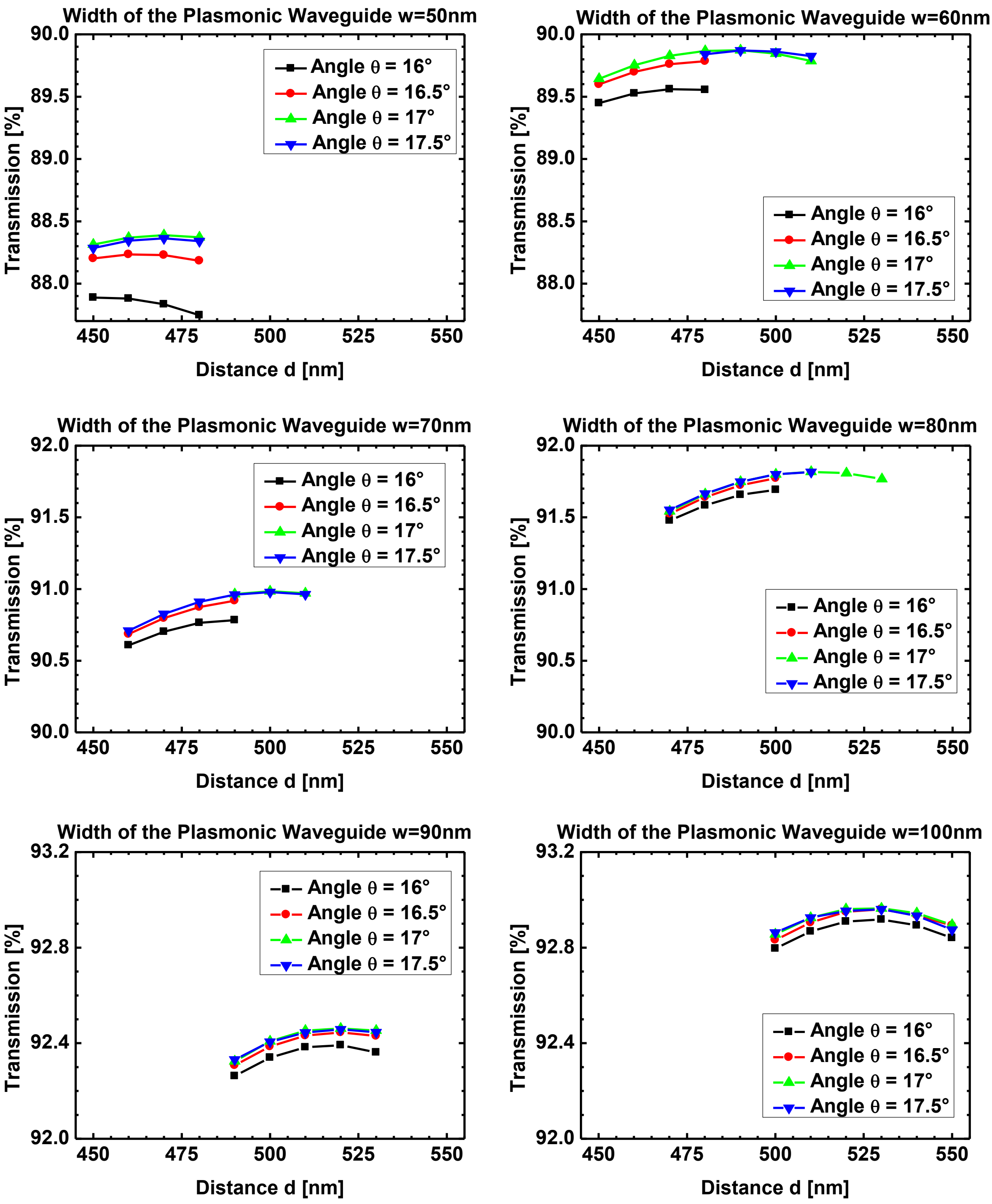

Figure 3 Transmission of DWG —PWG for different widths of the plasmonic from w = 50nm to w = 100nm

Below in the Figure 4, we summarize the results of the Figure 3 by plotting the distance *d* and tapering angle θ corresponding to the maximum conversion efficiency. It can be seen that the coupler provides the maximum coupling efficiency for the certain silicon tip angle of 17 degrees. Slight dependence of the optimum distance *d* on plasmonic waveguide width *w* can be seen. In all the cases the normalized transmission exceeds 85%, see Fig. 3(b), which makes such approach of SPP excitation unique.

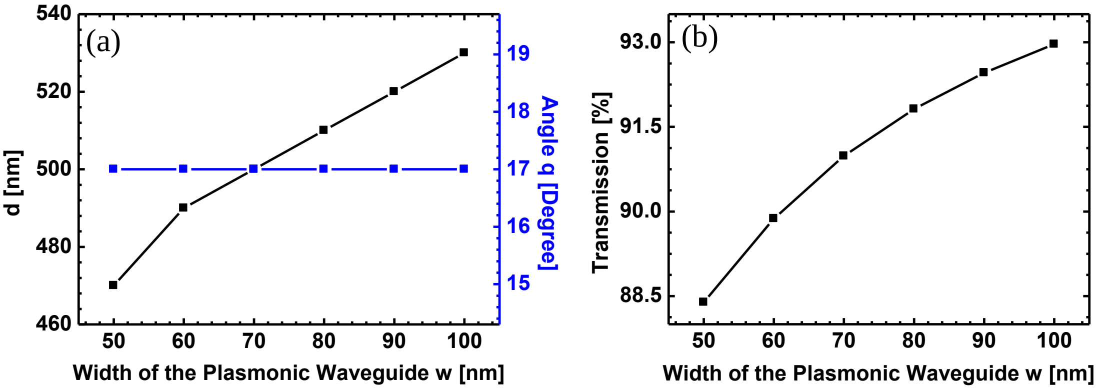

Figure 4 The optimized couplers geometry for various plasmonic waveguide widths *w*. (a) Optimized silicon tip angle θ and distance *d*. (b) Transmission corresponding to optimized structure

We have validated the results obtained for 2D slab structure for 3D realistic mode converter by performing full vectorial 3D FIT simulations, see Figure 5. The transmission dependence on taper angle θ and distance *d* for several plasmonic gap widths can be found in Figure 6. It can be seen that the optimal geometries differ slightly from the 2D case, only for a width of the plasmonic waveguide of 50nm and the deviation of the angle θ of the tapered silicon is from about 5°. It can be seen that even in the case of 3D real structure the high transmission is guaranteed with only few percentage of transmission penalty relative to 2D case. Even more surprising is the fact that the difference between transmissions for a width of the plasmonic waveguide of 50nm and 80nm is only

,0.4%.

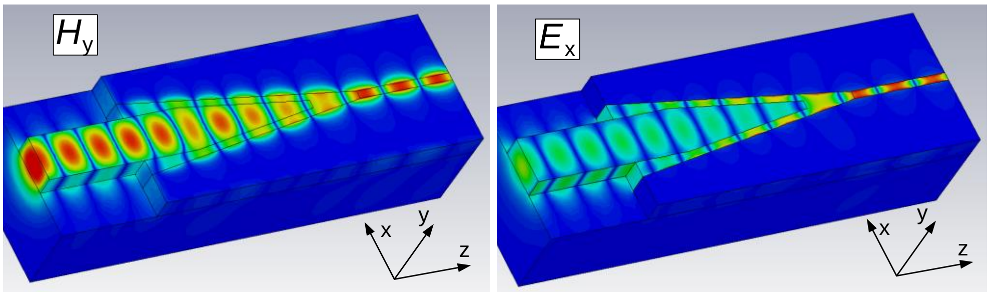

Figure 5 H_y and E_x component of the electromagnetic wave propagating through the plasmonic coupler (3D).

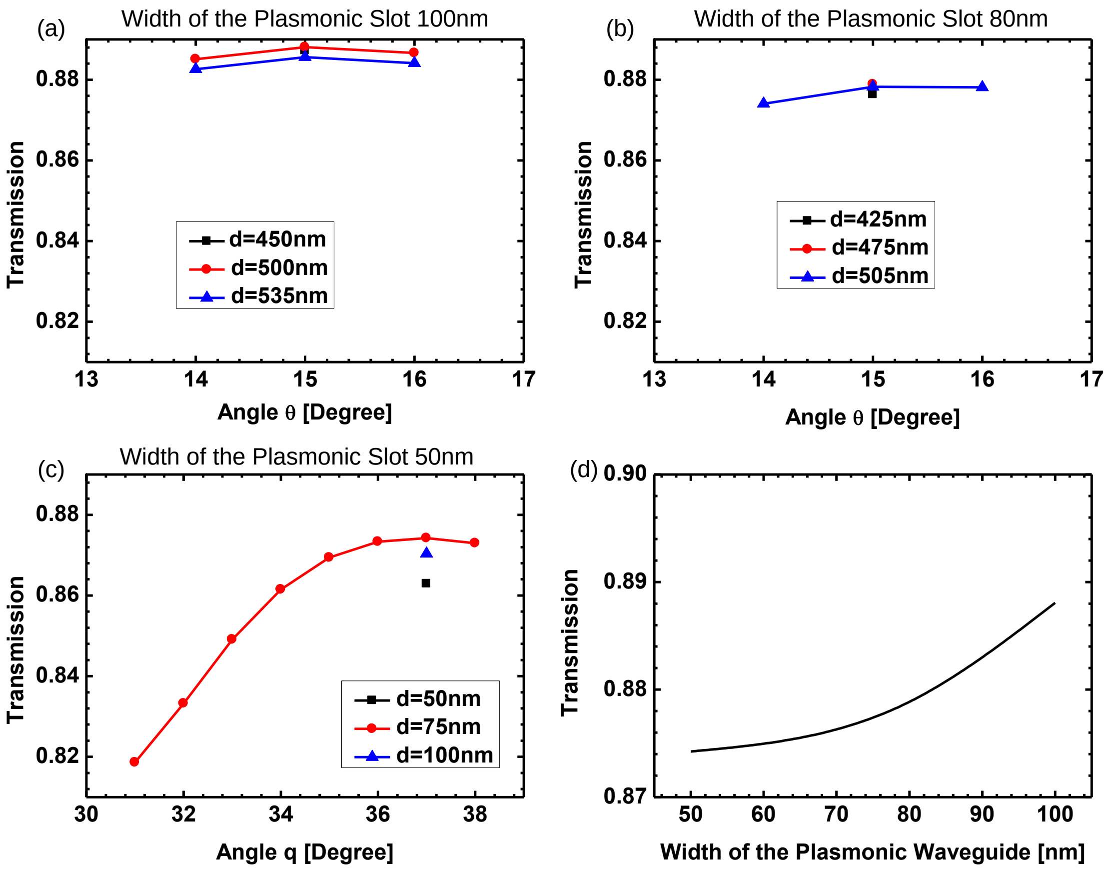

Figure 6 (a) –(c) the transmission from photonic to plasmonic with different geometries in 3D. (d) the transmission for the optimal geometry with different widths of the plasmonic waveguide for 3D.

An example of the geometrical parameters of the 3D realistic coupler can be found in Table 1.

Table 1 The geometrical parameters of the coupler for 50nm plasmonic slot width

SOI device layer thickness	220nm
Silicon waveguide width	500nm
Plasmonic slot width	50nm
Distance *d*	75nm
Angle θ	36°
Efficiency of a single coupler	87%

1.2 Fabrication methods

The mode converters have been fabricated as a part of the modulator fabrication [2]. The modulators with various device lengths and with a slot size of 140 nm and 200 nm are fabricated on silicon on insulator (SOI) platform, where the silicon nanowire waveguides are used as access waveguides. The fabrication procedure is described in Milestone 11, "Fabrication of plasmonic modulator on a SOI platform" and Deliverable 3.4, "Report on fabrication of modulators". Light is coupled into the silicon nanowire using standard diffraction grating couplers. Photonic mode guided through the silicon nanowire subsequently excites the gap surface plasmon polariton mode in the modulator section. In the end of the modulator section the plasmonic mode is back converted in photonic mode. Light is coupled out from the chip using second grating coupler. Optical and scanning electron microscope images of the first generation device with device length of 34 μm and the slot size of 200 nm are given in Fig. 1(a) and Fig. 1(b), respectively.

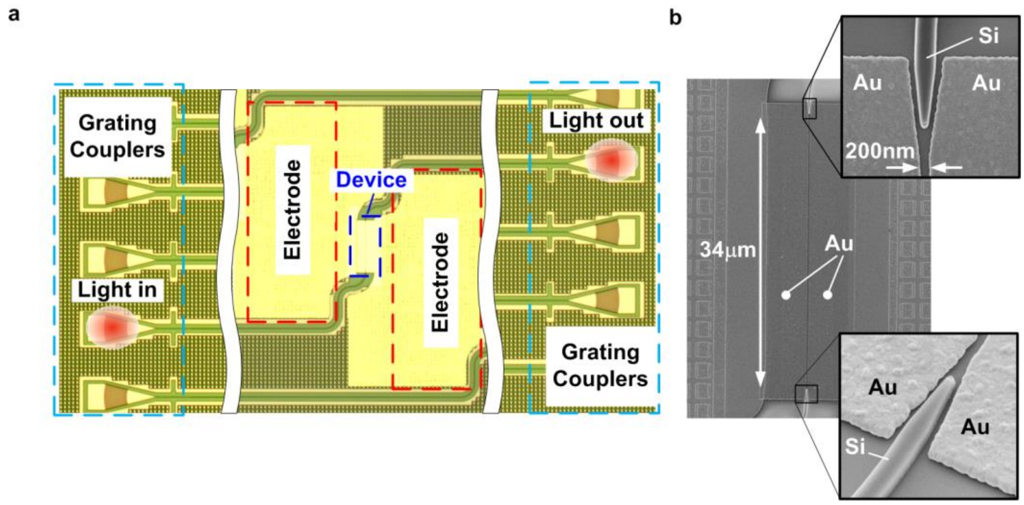

Figure 7 Fabricated plasmonic phase modulator on silicon on insulator platform. (a) Optical microscope image of the device. Silicon nanowire waveguides are used as access waveguides for the plasmonic modulator. Light is launched in and out from the chip using grating couplers. (b) Scanning electron microscope image of the modulator with a length of 34 μm and a slot size of 200 nm. Metallic tapers are used for photonic to plasmonic mode conversion.

Characterization of the fabricated phase modulators is performed at the KIT laboratory and the overview of the results is presented below.

1.3 Characterization results

We used the experimental setup given in Figure 8 for passive optical characterization. Light with from a tuneable laser source (TLS) is coupled into the device using a single mode fibers and a diffraction grating coupler. The transmitted optical power at the output of the device is measured with optical spectrum analyser (OSA). We measured the optical loss of the modulator section by taking an equal-length of SOI strip waveguide as a reference. Example of the transmission spectrum of 34 μm long plasmonic modulator with a slot size of 200 nm is given in Figure 8. The average total loss is 12 dB (black solid line), close to the theoretically expected value (blue dashed horizontal line).

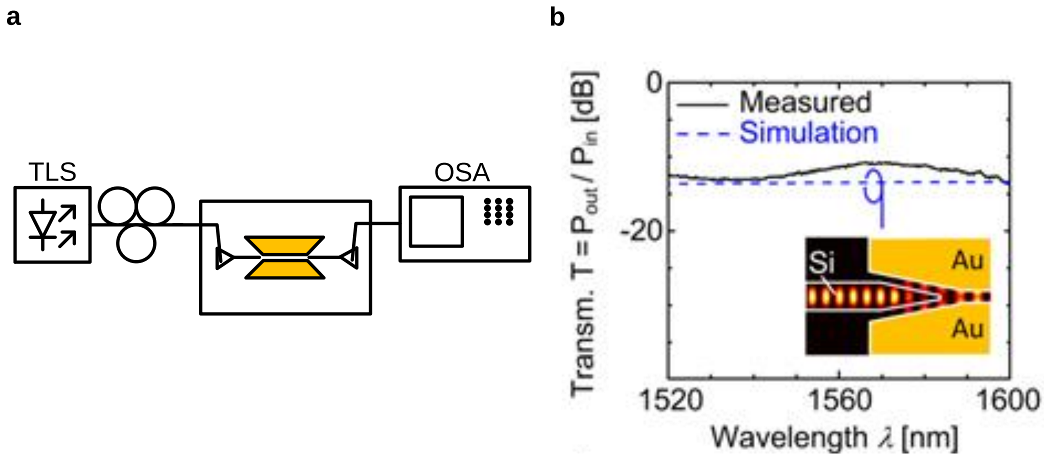

Figure 8 The experimental setup used for passive optical characterization and the transmission spectrum of the plasmonic phase modulators. (a) The experimental setup used for measuring the optical losses of the device. Light from the tuneable laser source (TLS) is launched into the chip and the transmission spectrum is measured at the output using optical spectrum analyser (OSA). (b) The transmission spectrum of the 34 µm long device with a slot size of 200 nm, black solid line. The theoretically expected transmission spectrum is given in the blue dashed line.

We have performed an SPP coupling loss estimation on our second generation of plasmonic modulators with a slot size of 140 nm. A good alignment and a desired 140 nm slot size have been achieved for the modulators with a length of 1 µm, 29 µm and 44 µm. We used the measured losses at the wavelength of 1550 nm to derive the propagation loss and the coupling loss of our modulators. By fitting the total loss versus device length dependence with a linear function we could estimate that the coupling loss and the propagation loss at 1550 nm wavelength, see Figure 9. The coupling loss in our second generation device is reduced below 1 dB. The propagation loss in the modulator with a slot size of 140 nm is 0.52dB / µm which is very close to theoretically expected value of 0.48dB / µm.

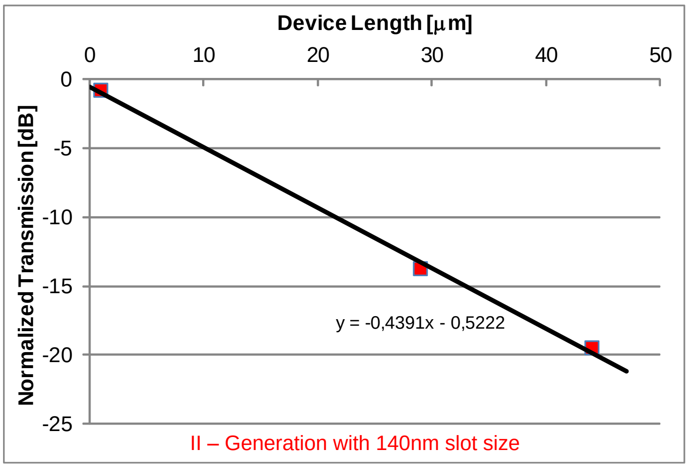

Figure 9 Measured power transmission at the wavelength of 1550nm for plasmonic modulators with various lengths. Performing linear fit we can estimate the SPP coupling and propagation losses in the modulator.

2. MMI based mode converter

Two configurations of MSWs have been reported in literature with either vertically or horizontally orientated slots as shown in Figure 10 (a) and Figure 10 (b), respectively[3]. When MSW structures are used as modulators it is of particular importance that the opening *h* between the metals is designed to be small, i.e. below 100 nm and that the width w is larger than 150nm, in order to achieve a strong field enhancement in the slot. However, fabrication of a metallic slot in Figure 10 (a) with a large w / h aspect ratio as well as excitation of its gap SPP becomes challenging. Alternatively, the horizontal MSWs of Figure 10 can more easily be fabricated with a large aspect ratio by means of a “bottom-up” fabrication approach.

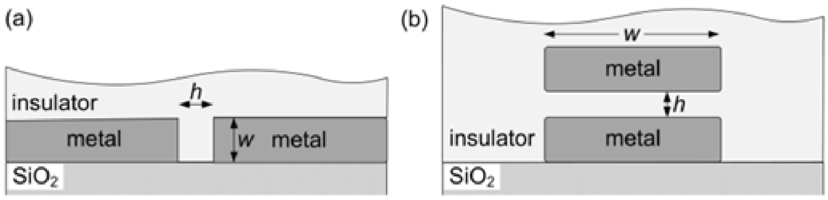

Figure 10 Metallic slot waveguides in two different configurations. Vertically oriented (a) and horizontally oriented (b) metallic slot waveguides.

Here, we study a novel coupling scheme between a silicon nanowire and a horizontal metallic slot waveguide with a broadband conversion efficiency of more than 85% [*A. Melikyan, et al., Optics Letters, to be submitted*]. Particularly, we show that a photonic mode of the silicon strip waveguide can be fully converted into a gap SPP of a sub - 50 nm metallic slot filled with insulator materials with refractive indices of 1.44, 1.6 and 1.7. We also discuss the influence of various fabrication errors on the coupler performance. The proposed converter can be used in various plasmonic devices where an efficient and controllable excitation and extraction of the gap SPP is needed.

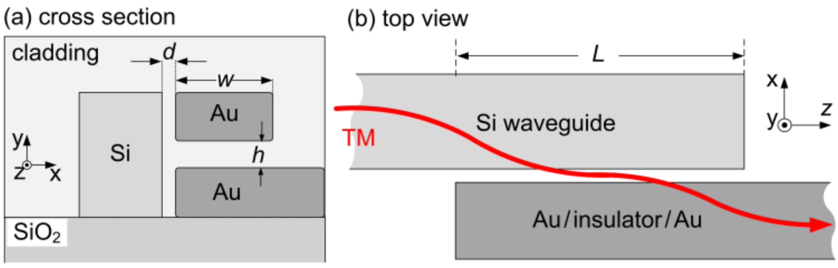

Figure 11 (a) Cross section and (b) top view of the suggested coupler. The TM mode launched into the silicon nanowire couples to a plasmonic waveguide via a coupling section of length *L*.

The operation principle of the proposed mode converter is based on similar ideas as the multimode interference couplers (MMI), see Figure 11. A photonic mode propagating through a silicon waveguide excites supermodes in the photonic/plasmonic MMI based coupling section (CS) of a length *L*. By properly selecting the length *L* and other geometrical parameters gap SPP can efficiently be excited in the end of CS. Depending on the application, the silicon nanowire can either be terminated after the CS or extended beyond this point.

To optimize the device’s performance we use the simplified EigenMode Expansion (EME) method [4]. Figure 12 shows the conversion efficiency $c_{\mathrm{MSW}}^{\mathrm{CS}}(z)$ versus the z coordinate for a distance *d* of 20 nm (red) and 60 nm (black). The maximum value of $c_{\mathrm{MSW}}^{\mathrm{CS}}(z)$ is taken as the best conversion efficiency and the corresponding z – coordinate is the respective optimum CS length *L*. As can be seen, the distance *d* mainly influences the coupling length *L*. The larger the distance *d* the longer the coupling length *L*.

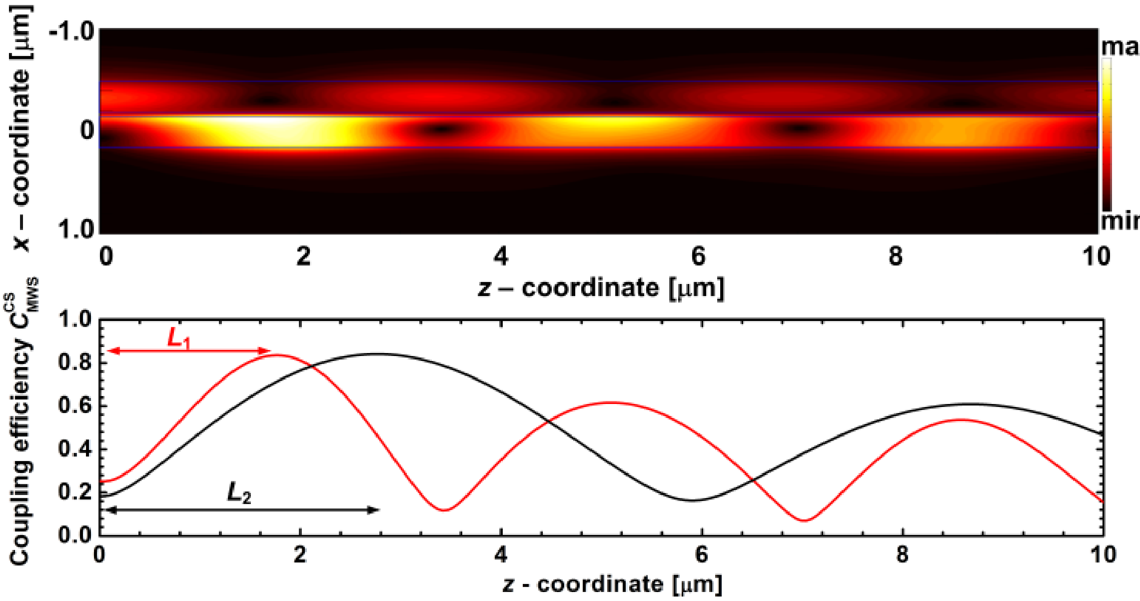

Figure 12 Electrical field distribution in the mode converter with a width *w* of 300 nm, slot height of *h* of 60 nm is given for an organic cladding with a refractive index of 1.7. The conversion efficiency is given as a function of a length *L* for two different distances *d* of 20 nm (red) and 60 nm (black).

In Figure 13, the conversion efficiency and the coupling length as a function of the distance *d* and the slot height *h* are given for MSWs with a width *w* of 200 nm for various cladding materials. Glass with a refractive index of 1.44, see Figure 13 (a), (b), and organic materials with refractive indices of 1.6, see Figure 13 (c), (d), and 1.7, see Figure 13 (e), (f), are considered as cladding materials. For all three types of cladding materials, conversion efficiencies exceeding 85 % can be achieved for MSWs with sub-50nm slots. Moreover, by varying geometrical parameters e.g. the distance d, the conversion efficiency can be tuned. This might be needed e. g. in the case of plasmonic coupling scheme shows a great tolerance to fabrication errors in defining the length *L*.

To investigate how the performance of the proposed mode converter depends on the operating carrier wavelength, we investigate the mode conversion mechanism in a converter with a silicon dioxide cladding by finite difference time domain (FDTD) method simulations. In this particular simulation a metallic slot height *h* of 30 nm and a distance *d* of 60 nm have been chosen. A continuous silicon nanowire is used with a CS length of 2 × *L* of 6.8 µm, as plotted in the inset of Figure 14. Transmission and reflection spectra are given in Figure 14. The wavelength dependence of the optical properties of Au is taken into account by the Drude model. No strong resonance behaviour is seen in the optical response of the mode converter. The operating wavelength range of the proposed device is in the range of 50 nm, which is comparable to the one reported for metallic taper mode converters.

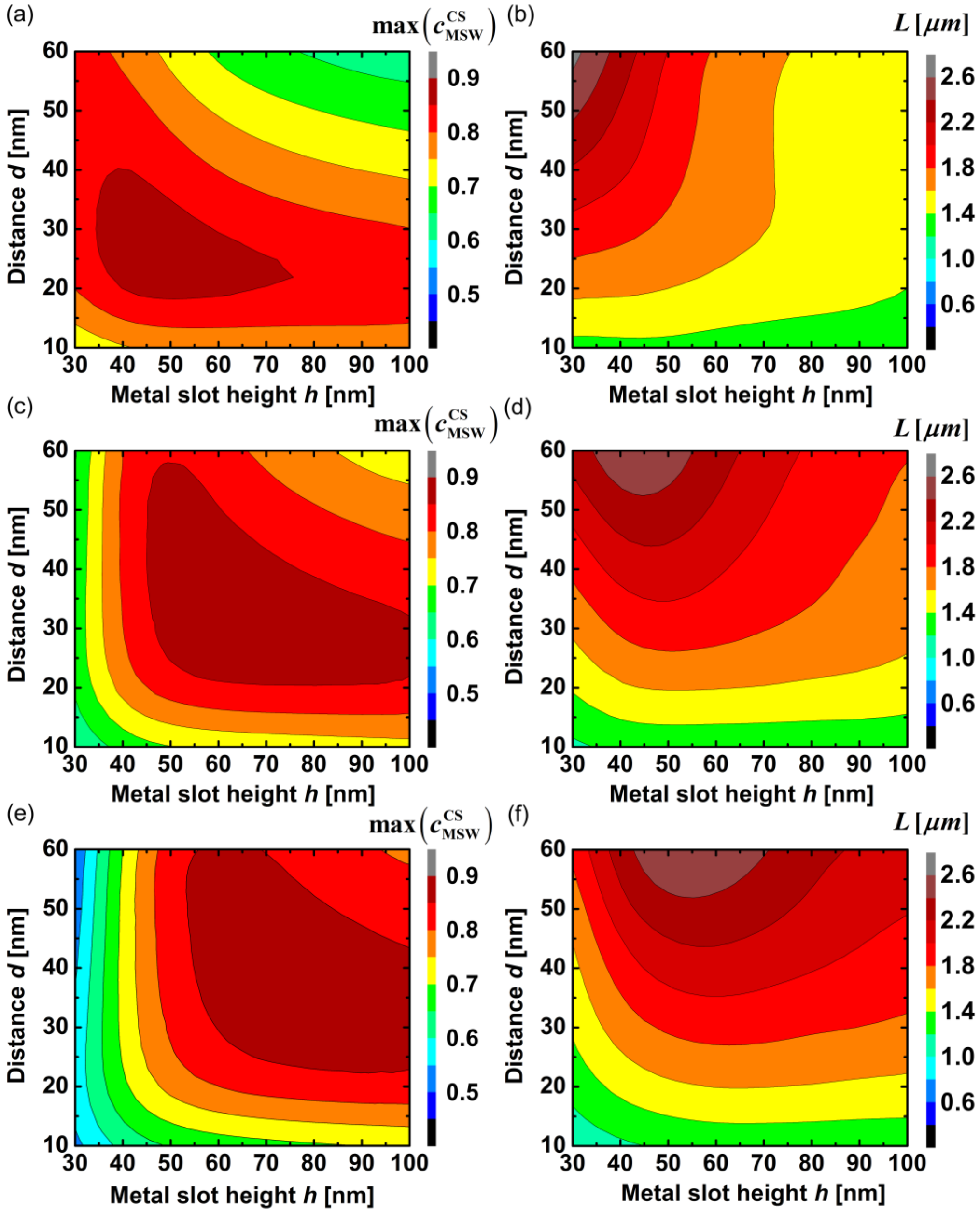

Figure 13 Conversion efficiency $c_{\text{MSW}}^{\text{CS}}$ (a), (c), (e) and optimum CS length L (b), (d), (f) for a MSW with a width w of 200 nm and for various cladding materials: (a) and (b) for Glass, (c) and (d) for organic materials with refractive indices of 1.6 and (e) and (f) for refractive index of 1.7.

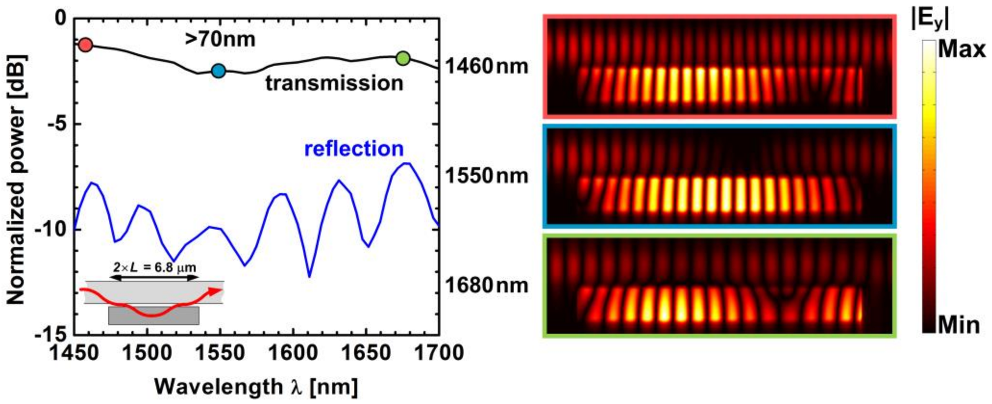

Figure 14 Transmission and reflection spectra in the converter with a height *h* of 30 nm, a distance *d* of 60 nm and a cladding material with a refractive index of 1.44. The dip in the transmission shows the good photonic / plasmonic mode conversion, in which case the Ohmic losses are the highest. In addition, the electric field distributions for three different carrier wavelengths are given in the right side. It can be seen that the photonic mode is fully converted in a gap SPP in the case of 1550 nm wavelength.

To conclude, we report on a novel photonic to plasmonic mode converter for silicon photonics. The approach provides more than 85 % of conversion efficiency for a gap SPP of a horizontal metallic slot waveguide with a sub-50nm slot filled with various insulator materials. The proposed mode converter does not exhibit any resonant behaviour and can be operated in a wide wavelength range. It requires simple "bottom-up" fabrication approach and shows a good tolerance to fabrication errors.

References

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