# Development of Plasmonic Slot Waveguide on InP Membrane

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*In this paper, we demonstrate a plasmonic slot waveguide on the InP membranes on silicon (IMOS) platform. Simulation and experimental results show this component features low insertion loss, low propagation loss and small footprint.*

## Introduction

InP membrane on silicon substrate (IMOS) is a versatile platform to combine both passive and active components in one optical layer. The high refractive index contrast of the IMOS platform leads to higher mode confinement and reduced dimensions of components, compared to traditional substrate-based InP photonic integrated circuits (PICs) [1]. Data communication is one of the major areas in which PICs can play a crucial role. One of the essential components of communication systems is a compact, efficient and high-speed optical modulator.

Plasmonic based components have been proposed as an alternative to conventional approaches to transfer data fast, with low-energy drivers and small footprint. Recent advances in plasmonic modulators have shown potential of these structures to reach modulation bandwidth beyond 170 GHz [2, 3]. Among all plasmonic modulators, the plasmonic-organic hybrid (POH) approach allows highest modulation bandwidth thanks to the combination of the metal slot waveguide with the fast electro-optic (EO) polymers. Here, we demonstrate a plasmonic slot waveguide for the first time on the InP membrane. The slot of this structure is filled with an EO polymer and can be used as a high speed phase shifter in a Mach-Zehnder configuration.

## Design and simulation

A plasmonic slot waveguide is presented here which is composed of a metal-insulator-metal (MIM) plasmonic structure coupled with conventional InP membrane waveguides, as depicted in Figure 1.

Light from a fiber couples into the conventional membrane waveguide with a surface grating coupler. A taper converts the waveguide mode to the surface plasmon polariton (SPP) mode in a 200 nm wide slot. SPP mode propagates through the slot and couples back to the waveguide mode through the second taper, and couples out with another surface grating coupler.

The plasmonic slot waveguide is simulated with a three-dimensional (3D) finite-difference time-domain (FDTD) method. A complete layer stack has been modeled in 3D, as shown in Figure 1(a).

In order to avoid complexity of the 3D model, surface grating couplers are not included. Instead a light source is placed at the input of the waveguide, which is indicated by a yellow arrow on the Figure 1 (b). Additionally, a single layer of gold is considered as the metal stack, which is different from the fabricated one. The refractive index of the background of the simulation area set to the refractive index of the EO polymer equals to

1.7. This is because the EO polymer covers everything, including the metal slot in the actual sample.
There are two primary design parameters that dominate the coupling efficiency of the mode in the semiconductor taper and SSP mode of the metal slot: the metal slot width and the taper length.
An optimization is performed to obtain a high coupling efficiency and a low reflection. The TE fundamental mode with a wavelength of 1550 nm was launched in the input waveguide and then tapered down to couple to the metal slot SPP mode.

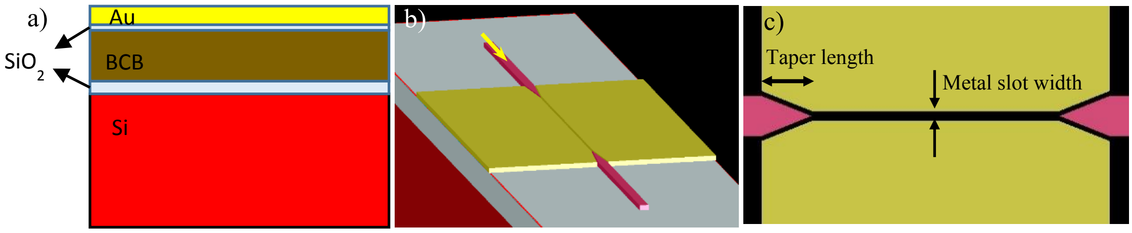


*Figure 1. (a) Layer stack of the 3D model. (b) 3D perspective view of the model, the yellow arrow is the place of the optical source. (c) Variables which have to be optimized.*

The optimized taper length values obtained for the two metal slot widths of 100 and 200 nm are 439 nm and 558 nm, respectively. In the Figure 2, the optical field distribution over the coupling region and on the metal slot cross section is depicted.

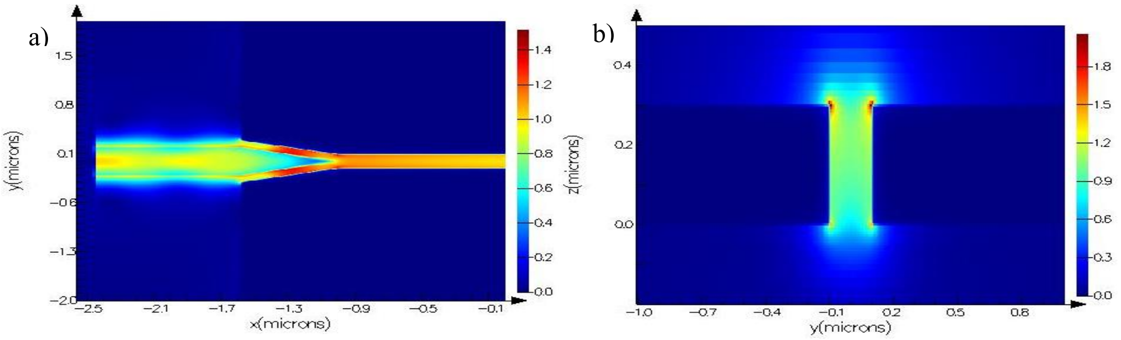


*Figure 2. (a) Electric field distribution of the optical mode lunched into the waveguide. (b) Electric field distribution of the SPP mode at the metal-insulator-metal plasmonic slot.*

## Fabrication

The plasmonic structures are patterned using electron beam lithography (EBL). These structures include an input and an output grating coupler connected to semiconductor waveguides which guide the light to the tapers in order to couple and decouple the light to and from a metal-insulator-metal slot. Fabrication was done on an InP membrane bonded to a silicon substrate (IMOS) with BCB polymer [2]. The thickness of the membrane is 300 nm. The fabrication involves four EBL exposures. The first exposure is to define the markers of the pattern for alignment purposes. Then, the exposed pattern of markers is etched in the semiconductor with a single step etch of 260 nm. In the second exposure, both waveguides and focusing grating couplers are defined and subsequently etched in the semiconductor (The etch depth is 260 nm). At the third exposure, the 40 nm of the semiconductor remaining from the second exposure etch, is removed from the areas where metals are going to be placed. This step is done to electrically isolate each device from the rest of the chip. In Figure 3(a); SEM image of the sample after the third exposure is shown. The last exposure is to pattern the resist for deposition of the metal layer, which consists of 30 nm Ni / 50 nm Ge / 250 nm Au, by Electron Beam Evaporator. Finally, as shown in Figure 3 (b), a lift-off process is used to create the plasmonic metal slots. Although the dimensions of the fabricated sample deviated from the original design, measurements could still be performed. Metal slots of 200 nm width could be reproducibly opened, with sufficient alignment with respect to the taper couplers and a small deviation from the original design width, as shown in Figure 3(c). The last step is to spin coat a layer of EO polymer on top of the fabricated sample.

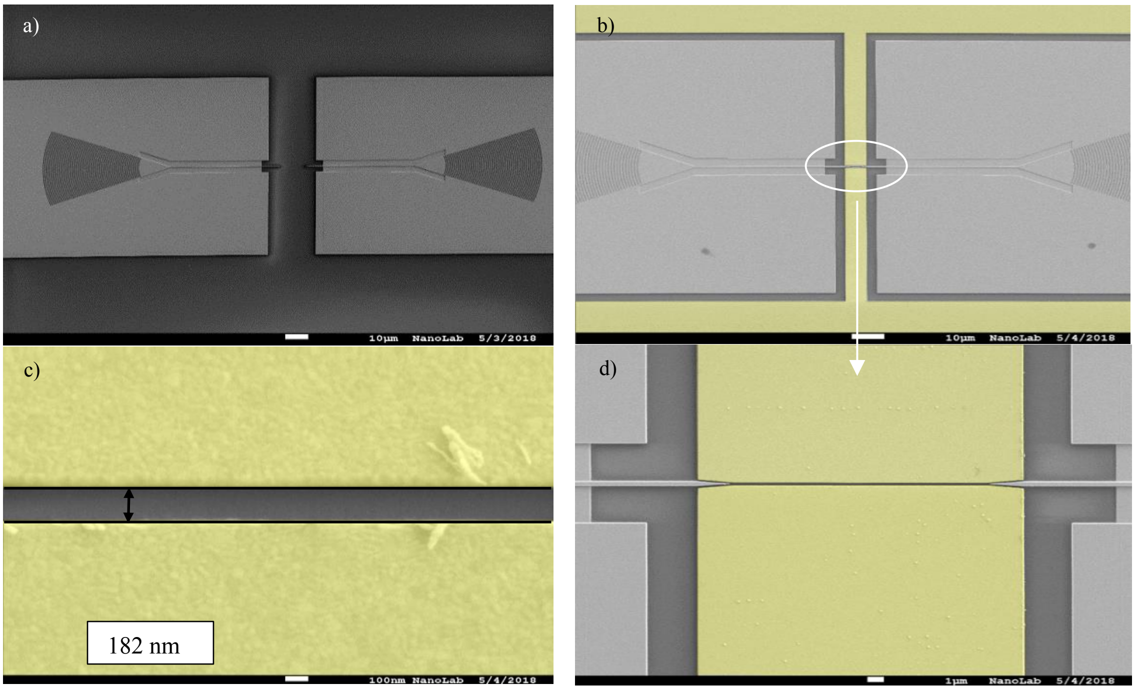


*Figure 3. (a) SEM picture after third exposure when the waveguides and grating out couplers were patterned and footings of the semiconductor were removed from the areas where metals going to be placed. (b) SEM picture, with false colors, of the plasmonic slot waveguide connected to two grating out couplers. (c) SEM picture, with false colors, which shows the dimension of the fabricated metal slot. (d) Zoom-in image of the plasmonic slot waveguide.*

## Measurement results and analysis

In order to study the fabricated structure, optical transmission measurements have been performed to characterize the performance. On the experimental setup laser light was coupled to the input grating coupler and collected from the output grating coupler. Transmission spectra have been obtained by sweeping a tunable laser across an optical wavelength range of 200 nm, from 1440 to 1640 nm.

In Figure 4, transmission spectra are presented. The minimum insertion loss was obtained at 1510 nm, which is coincides with the center wavelength of the surface grating couplers. In Figure 5, a linear fit with minimum insertion loss from the structures with different metal slot length, was made to obtain the propagation loss into metal slot and coupling loss from the semiconductor taper and metal slot. A low propagation loss in the plasmonic slot equal to 0.43 dB/µm is achieved which is comparable to the state of the art achievements for plasmonic waveguides [2, 3 and 4].

The simulated value for the propagation loss is equal to 0.5 dB/ µm, which is slightly higher than the experimentally obtained value. This discrepancy is anticipated to come from simulation simplifications like not considering: metal sidewall slopes, actual metal layer stack, metal layer stack thickness, exact effective refractive index of the polymer and fabrication deviation from the designed values. A more detailed model is needed to predict the propagation loss more accurately.

A coupling loss of 4.2 dB from semiconductor taper to the metal slot is achieved experimentally, while the simulated value is 1.1 dB. We suppose this difference is coming mainly from imperfections, which are roughness on the sidewalls of the taper and misalignment of the taper tip with the center of the metal slot. However, still this coupling loss is in the same order as the reported values [2, 3 and 4].

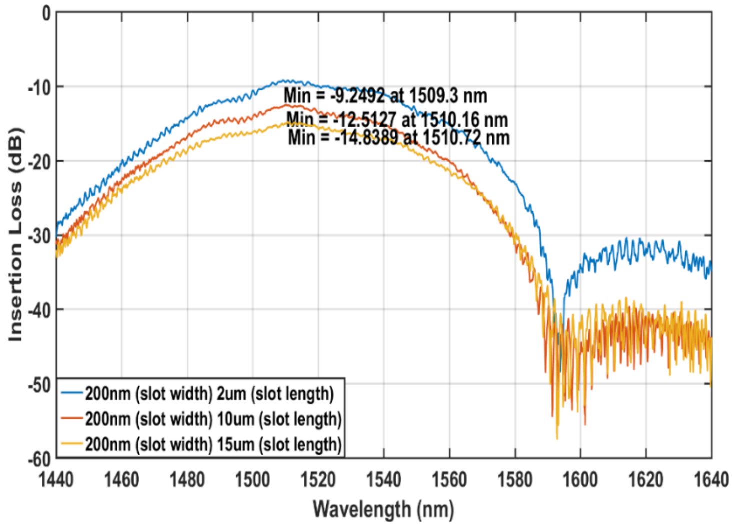


*Figure 4. Measured insertion loss spectra for three different metal slot lengths equal to 2µm, 10µm and 15µm.*

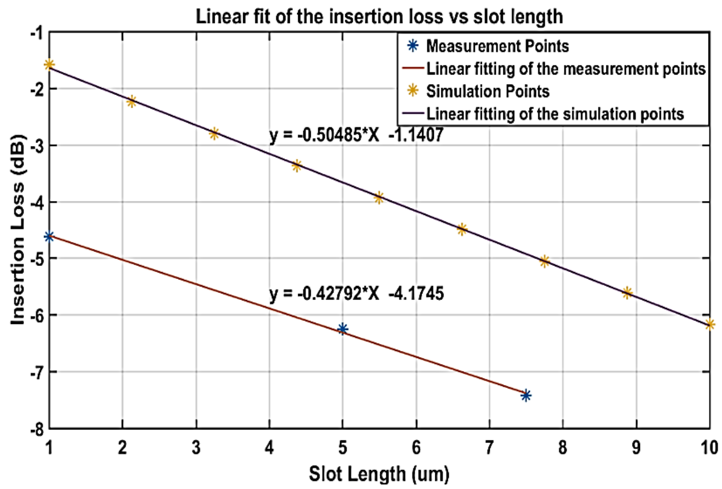


*Figure 5. Linear fit of the measured and simulated points of minimum insertion loss versus metal slot length.*

## Conclusion

In conclusion, we have studied a plasmonic slot waveguide structure. This structure was fabricated on the IMOS platform. According to the findings, a low propagation loss is achieved in the 200 nm wide plasmonic metal slot equal to 0.43 dB/µm. However, the coupling loss from the optical mode in the waveguide to the SPP mode in the metal slot is higher than designed, due to fabrication challenges/imperfections. Furthermore, improvements can be achieved by improving the fabrication processes and replacing the gold electrodes with e.g. silver to lower the optical losses.

## References

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