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

Decision on an optimized structure for plasmonic modulator

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Executive Summary

This document shall incorporate (all) rules procedures concerning the technical and administrative management of the project and is therefore to be updated on a regular basis. Please look at www.navolchi.eu regularly for the latest version.

Change Records

Version	**Date**	**Changes**	**Author**
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Introduction

Surface plasmon polariton is an electromagnetic surface wave at conductor\insulator interface coherently coupled to an electron density oscillation in the conductor. Because of its combined electronic and photonic nature, SPPs can be confined in a volume smaller than the diffraction limit and thus paving the way to sub-diffraction integrated optics.

Electro-plasmonic (EOP) modulator is a device which employs the surface plasmon polaritons to encode the electrical information onto the electromagnetic wave. In a simplest case surface plasmon polariton can be described with a harmonic function with given amplitude (A), frequency (ω), phase (ϕ) and polarization, which gives the orientation of electric field.

$$E(t) = A(x)\cos(\omega_0 t + \phi(t)) \tag{1.1}$$

Similar to the conventional optics, the electrical signal can be encoded onto the any of the characteristic quantities of SPP such as its amplitude, phase or frequency (SPPs only exist with TM polarization; therefore, the discussion of the modulation of polarization state of SPP will be omitted). Depending, on the requirements in the optical link one or even the combination of these modulation formats is desirable. The EOP modulator is one of the key components in the chip-to-chip plasmonic link which is located in the transmitter side and is responsible for transformation of the digital information from electrical domain to optical domain.

It is known that one of the possibilities of frequency shift keying is employing a phase modulator and driving it with a triangular voltage pulse. Thus, we will only focus ourselves in two modulation schemes, namely, direct amplitude modulation employing Surface Plasmon Polariton Absorption Modulator(SPPAM)[1-2] and phase modulation with Plasmonic Phase Modulator (PPM) [3].

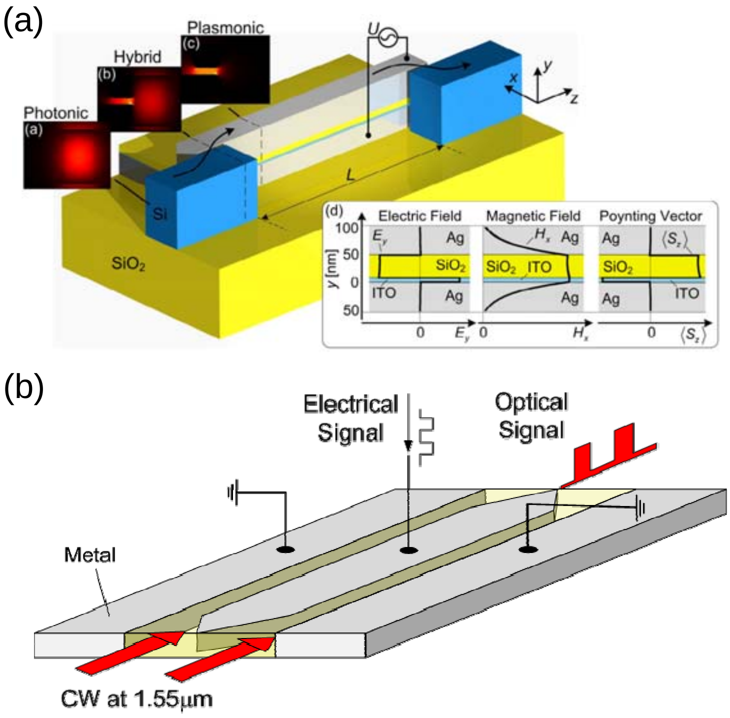

Figure 1 Plasmonic modulator approaches engaged by NAVOLCHI. (a) Surface plasmon polariton absorption modulator [1] and (b) plasmonic phase modulator[3].

Surface plasmon polariton absorption modulator

The configuration of the suggested SPPAM is given in Fig. 1(b). It comprises a silicon strip waveguide on a buried silicon-oxide layer. The central plasmonic section consists of a dielectric layer and a thin metal-oxide layer sandwiched between highly conductive metal layers, see Fig. 2. The metal layers serve as SPP waveguides and as electrodes for applying an electric field across the dielectric. The absorption coefficient of SPP in such structure has been shown to be strongly dependent on free electron density in ITO. Therefore, modulating the free carrier density of ITO with external voltage one can modulated the intensity of SPP at the output of the modulator [1].

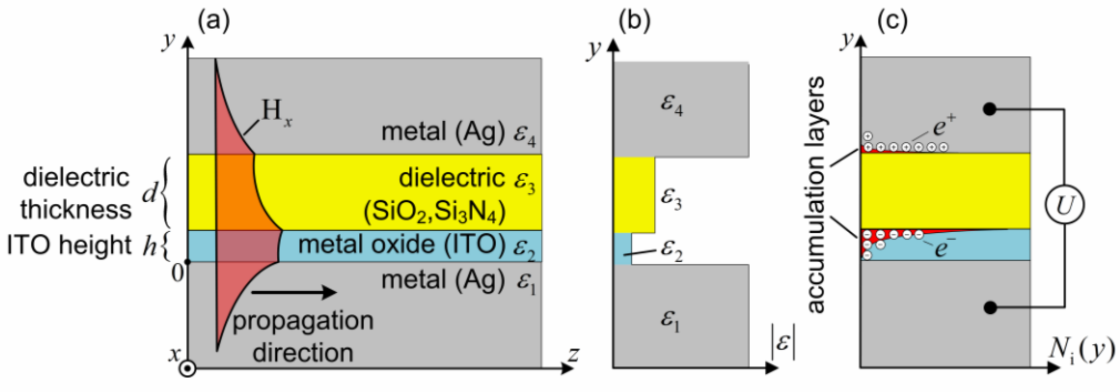

Figure 2 Plasmonic structure with metal/dielectric/metal-oxide/metal layers.

The modulator performance strongly depends on the middle active plasmonic section particularly on the dielectric permittivity and thickness of the insulator layer, on the thickness of ITO as well as on the length L. Main characteristics of the absorption modulator are its insertion loss, driving voltage, extinction ratio as well as its footprint. Limiting ourselves on 1V driving voltage, the device length $L = L_{1dB}$ can be found necessary for having an extinction ratio of 1dB. Thus, it makes sense to define a figure-of-merit (FoM)

$$\mathrm{FoM} = \frac{L_e}{L_{1\mathrm{dB}}} \qquad (1.2)$$

where L_e is the propagation length of SPP and gives the length after which the intensity of the SPP has decreased to a fraction of 1 / e of the initial intensity. L_{1dB} is the length necessary having 1dB extinction ratio for the applied voltage of 1V. The larger the FoM, the better the performance is, i.e. the lower the propagation losses are for a 1 dB extinction ratio and an applied voltage of 1V. The FoM of SPPAM has been calculated in the case of various geometrical and material properties and compared with plasmonic phase modulator in order to make a decision on the modulator type to be used in the plasmonic interconnect architecture.

Surface plasmon polariton phase modulator

Another modulator approach investigated within NAVOLCHI is the surface plasmon polariton phase modulator. The modulator design is very similar to the slot line transmission line introduced few decades ago in microwave community. Unlike to the conventional slot line, plasmonic slot waveguide has dimensions that are several orders of magnitude smaller than its microwave equivalent. This is a result of the fact that going from microwave to optics frequency of electromagnetic wave is increased by several orders of magnitude.

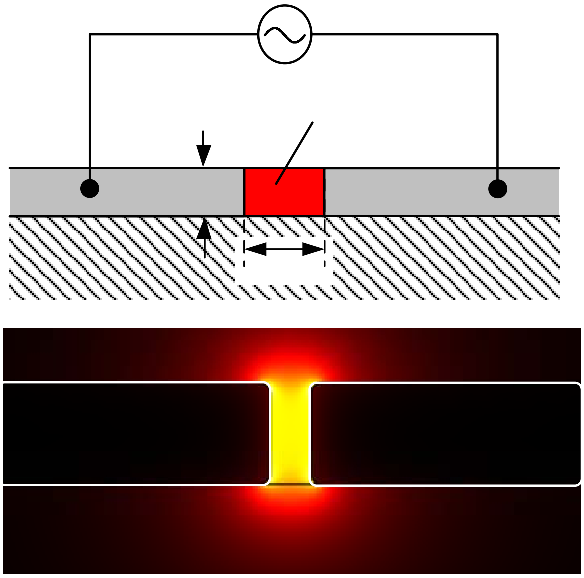

Figure 3 Plasmonic slot waveguide as candidate for SPP based modulator.

In Fig. 3 the typical mode profile of SPP at metallic slot structure is shown in the terms of absalute value of electric field. It can be seen that the field is strongly enhanced in the insulator layer sandwitsched between two metallic electrodes. Replacing the passive insulating layer sandwitsched between two metallic electrodes with an active material can convert the passive metallic slot waveguide into an electro-plasmonic modulator. Such a convertion is done by replacing the insulator layer with an linear electro-optically active material such as nonlinear optical polymer. In the case of phase modulator, figure-of-merit is defined similar to SPPAM replacing the $L_{1\mathrm{dB}}$ with L_π which descibes the required length of the phase modulator for having a accumulated phase shift of π in the case when the applied voltage U_{pp} equals to 1V

$$\mathrm{FoM} = \frac{L_e}{L_\pi} \tag{1.3}$$

The larger the FoM, the better the performance is, i.e. the lower the propagation losses are for having a accumulated phase shift of π in the case of applied voltage of $1\mathrm{V}_{\mathrm{pp}}$.

Results, Decision on Modulator type and its design

Figure-of-merits of both modulators are represented in Fig. 4. In the case of absorption modulator, the FoM is given as a function of the thickness of the insulating (SiO_2) layer for three different ITO thicknesses. The FoM of phase modulator is given for various slot size and metal thickness.

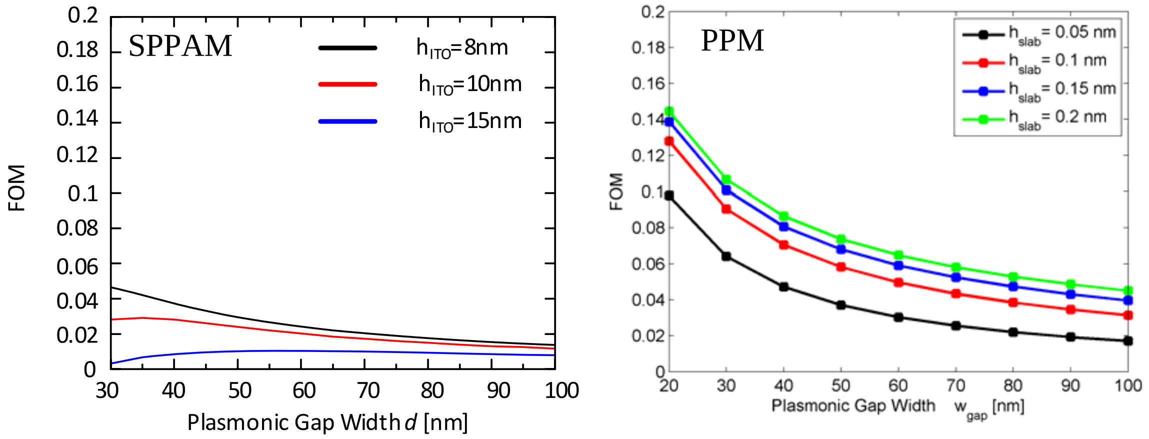

Figure 4 Figure of merits of (a) surface plasmon polariton absorption modulator (SPPAM) and (b) plasmonic phase modulator (PPM)

It can be seen that in the both cases reducing the separation of metallic electrodes increases the FoMs of the devices. This is a consequence of the fact that for the given voltage reducing the distance between metal electrodes results to enhancement of the driving electric field inside the active region due to the reciprocal relation between electric field and the distance between electrodes. Additionally, unlike to other optical modulator approaches, such plasmonic modulators exhibit optical field enhancement with reducing the distance between metal electrodes, which itself enhances the light-matter interaction consequently reducing the footprint of the modulator.

NAVOLCHI will focus its expertise on the plasmonic phase modulator approach because of its relatively large figure of merit. It can be seen from Fig. 4 that the modulator provides its best performance for the metal thicknesses larger than 100nm and for the slot size below 80nm. The possibility of the slot size smaller than 40nm is being omitted because of the fabrication limitation.

The decision is also supported by the fact that the plasmonic phase modulator is relatively easier to fabricate comparing to the absorption modulator. This can be seen by comparing the fabrication approaches of both modulators. The fabrication vision of the SPPAM can be found in the NAVOLCHI proposal *Part B, Fig. 1.3.4*. The process flow for fabrication of the PPM has already been introduced in the technical presentation of KIT in the NAVOLCHI Kick-off meeting, see Fig. 5.

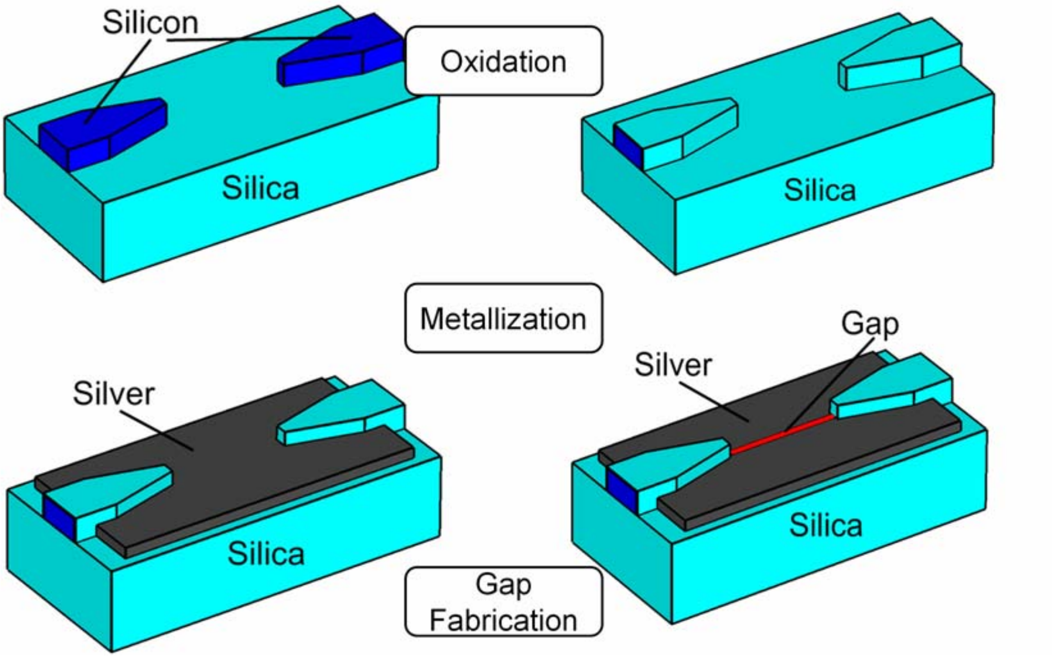

Figure 5 Process flow for fabrication of the plasmonic phase modulator

[1] A. Melikyan, N. Lindenmann, S. Walheim, P. M. Leufke, S. Ulrich, J. Ye, P. Vincze, H. Hahn, Th. Schimmel, C. Koos, W. Freude, and J. Leuthold, "Surface plasmon polariton absorption modulator," Opt. Express **19**, 8855-8869 (2011)

[2] A. Melikyan, T. Vallaitis, N. Lindenmann, T. Schimmel, W. Freude, and J. Leuthold, “A surface plasmon polariton absorption modulator,” in Conference on Lasers and Electro-Optics, p. JThE77 (2010)

[3] S.-I. Inoue and S. Yokoyama, “Numerical simulation of ultra-compact electro-optic modulator based on nanoscale plasmon metal gap waveguides,” Electron. Lett. 45(21), 1087–1089 (2009)