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Active Hybrid Plasmonic Modulator based on an Electro-Optic Material

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ABSTRACT

The development of Hybrid Plasmonic Electro-Optic Broad-Band Modulators with substantial modulation depth, compact design, and low power consumption has garnered significant attention not only from the scientific community but also from the industrial sector. These devices hold the potential to revolutionize on-chip optical interconnects. This paper demonstrates an ultra-compact and ultra-fast hybrid plasmonic EO modulator based on a monolayer of an active material called ITO. By electrically tuning the refractive index of ITO through an external electrical signal with a low operation voltage ranging from 0 to 4 volts, the device achieves a high modulation depth of ≈38% (transmission at ON state is ≈71.7%, while transmission at OFF state is ≈1.89%) and low energy consumption of (11.384-22.7) fJ/bit. Additionally, it features a compact footprint of 11 μm^2 at the telecommunication wavelength (1550 nm). These combined advantages, spanning a broad range of wavelengths, have the potential to enable novel architectures for on-chip optical communications.

Keywords: *Plasmonics; Electro-optic switch; hybrid waveguides; Photonic integrated circuits; SOI waveguides.*

1. Introduction

In the realm of photonic systems, high-speed, ultra-compact, and power-efficient electro-optic (EO) modulators play a pivotal role. These modulators are designed to alter the fundamental properties of light beam propagation in optical waveguides based on external electrical signals. Among various research endeavors, silicon-based modulators have gained significant attention due to their immense potential for future optical interconnections. Being compatible with the complementary metal-oxide-semiconductor (CMOS) fabrication standard and offering relatively low costs make them particularly appealing. However, the limited electric-to-optic conversion efficiency of silicon-based modulators hinders their modulation performance. As a result, there is an urgent need for new materials that combine CMOS compatibility with highly efficient electric-to-optic conversion, essential for advancing silicon-based modulator technology [1-4].

Different transmission rates have already been demonstrated using several modulator structures. Those modulators introduced high voltage-length product, high power consumption and high footprint over a small operating wavelength range. These limitations ultimately constrain the modulation bandwidth and power efficiency of the devices.

Various physical effects have been utilized for electro-optic (EO) modulation. However, typical modulator architectures, including silicon-based structures, high-quality resonant structures, and Mach-Zehnder structures, often struggle to optimize all modulator parameters simultaneously. These structures suffer from drawbacks such as narrow bandwidth, high energy consumption, and large size. Consequently, there is a need to develop new modulators that are both compact in size and broadband in their performance [5-8].

The Silicon photonics platform has attracted significant attention as a means of improving high-performance EO modulators. Furthermore, there is a growing focus on investigating advanced device designs that offer a smaller footprint, seamless integration with Si electronics, and reduced power consumption, all of which warrant further research endeavors. Plasmonics, a novel technological branch, emerges as a promising approach to bridging Nano-scale electronics and Micro-scale photonics. By addressing challenges within the diffraction limit, plasmonics provides solutions to delay time and limited bandwidth issues [9-10].

In the field of plasmonics, noble metals with negative permittivity, such as silver and gold, are employed to reduce the voltage-length product and enhance the modulator bandwidth simultaneously. The convergence of optics and electronics in the emerging field of plasmotronics is expected to usher in a new era of rapid data communications and computing, enabling simultaneous control of optical and electronic signals. Moreover, plasmotronics holds the potential to deliver devices with extremely compact spatial footprints and ultrafast operating speeds [11–12].
Combining plasmonics with photonics, semiconductors, and dielectrics achieves robust mode confinement while minimizing propagation loss to an acceptable level. This compatibility ensures that silicon-on-insulator (SOI) waveguides can be seamlessly integrated into complementary metal-oxide-semiconductor (CMOS) fabrication processes, which is a crucial advantage. This feature guarantees a cost-efficient environment for large-scale production of these integrated photonic devices [13-14]. This research paper presents an active modulation technique utilizing Electro-optic principles, which can be implemented using both silicon-on-insulator (SOI) and metal-oxide-semiconductor (MOS) waveguides. The modulation process in this research relies on a thin layer of indium tin oxide (ITO) positioned within the MOS waveguide. ITO is chosen as the active material due to its excellent index tunability, seamlessly integrated into the MOS waveguide layers.
The modulation mechanism involves altering the free carrier concentration of the ITO material that overlaps with the propagating optical mode. This, in turn, leads to a shift in the plasma frequency of the dispersion relation.
The optical properties of propagated wave (the propagation loss and the effective index) have modified due to the variations occurred in the refractive index of optical material. The swift energy transfer within the ITO facilitates a more robust nonlinear response. The shift in the optical properties of ITO, transitioning from dielectric-like to metallic-like behavior under an applied bias, offers novel opportunities for implementing plasmotronics modulators [15-17].

2. Modeling and Characterization of Hybrid Plasmonic Electro-Optic Modulator

Optical modulators are devices that enable the manipulation of light through electrical signals, essentially transforming electrical signals into optical signals. Subsequently, the light can be propagated through an optical waveguide or transmitted through free space. Based on the altered characteristics of light, we classify the modulator types accordingly. The modulator proposed in this paper is classified as an amplitude modulator, as it controls the power of transmitted light, and its operation relies primarily on the properties of the active material.

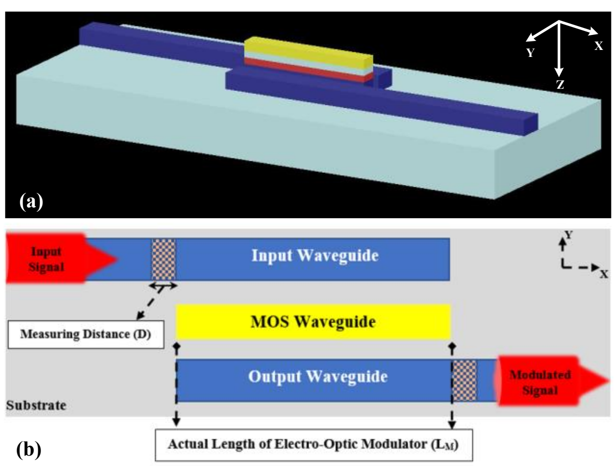

Figure 1: the structure of hybrid plasmonic electro-optic modulator a) 3D- view, b) 2D- YX view.

The proposed hybrid plasmonic electro-optic modulator consists of two identical Si arms act as input/output waveguides, they are separated by a MOS waveguide which is centered between them as illustrated in figure (1) and all of the three waveguides are printed on a substrate from silicon dioxide. The best algorithm for modeling plasmonic devices is finite-difference time-domain (FDTD), and the popularity of this algorithm is due to its efficiency in solving and analyzing a huge number of problems in a very short time.

This procedure depends on discretizing the time and space and hence the spatial and temporal derivatives in Maxwell's curl equations are replaced by finite difference quotients. The finite-difference time-domain (FDTD) algorithm is more efficient for large systems as the wanted processing memory changes only depending on the volume of the processing domain. The boundary conditions used in the numerical methods which established on the differential form of Maxwell's equations are enforced on the fields. The boundary has to reintroduce a homogeneous non lossy unlimited medium; or in other words, reduce the nonphysical reflections. For the sake of fix this trouble, the perfectly matched layer (PML) was inserted. It is a layer of lossy material with a perfectly matched interface that absorb the plane wave for all frequencies and all angles of incidence and polarizations [18-19]. Here, Lumerical FDTD Solutions, a software package, is used for solving 3D Maxwell's Equations using Finite Difference Time Domain method.

A group of essential factors should be measured to quantify the performance of plasmonic electro-optic modulator [20-21]. They are; transmission, modulation depth, energy consumption, modulation speed, and finally the design' footprint. These parameters are defined as follows;

$$\boldsymbol{Transmission}\,(\%) = \mathbf{100} * \left(\frac{\boldsymbol{Power_{Modulated\ Signal}}}{\boldsymbol{Power_{Input\ Signal}}}\right), \qquad (1)$$

$$\boldsymbol{Modulation\ Depth}\,(\boldsymbol{dB}) = \mathbf{10}\boldsymbol{Log}\left(\frac{\boldsymbol{Transmission_{ON\ State}}}{\boldsymbol{Transmission_{OFF\ State}}}\right), \qquad (2)$$

$$\boldsymbol{Modulation\ Bandwidth} = \left(\frac{\mathbf{1}}{\boldsymbol{RC}}\right), \qquad (3)$$

$$\boldsymbol{Energy\ Consumption}\ (\boldsymbol{or\ Energy\ per\ Bit}) = \left(\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{CV^2}\right), \qquad (4)$$

The parameters in equations (3) and (4) mainly depend on the capacitance ($\boldsymbol{C}$) of MOS waveguide which computed as follows:

$$\boldsymbol{C} = \left(\frac{\boldsymbol{\varepsilon_0\,\varepsilon_D\,W\,L_M}}{\boldsymbol{t}}\right) \qquad (5)$$

Where; ε_D and t are the permittivity and width of the dielectric, respectively. The modulator' length is represented by L_M; While W is related to the MOS' width. Finlay; ε_0 is related to the permittivity of free space. The working principle of electro-optic modulator including the design methodology, optimization process and the obtained results is presented in the next sections.

2.1 Design Parameters of Hybrid Plasmonic Electro-optic Modulator

This work presents a more compact and efficient hybrid plasmonic modulator, as illustrated in figure (1), which consists of: a) two identical Si arms act as input/output waveguides with dimensions of 400 nm in width and 340 nm in height, b) a MOS waveguide centered between the two Si- arms through which the actual length of plasmonic modulator is determined and has dimensions of 275 nm in width and 510 nm in height. The three waveguides are separated by a gap of 150 nm in width and all of them are printed on a substrate from silicon dioxide.

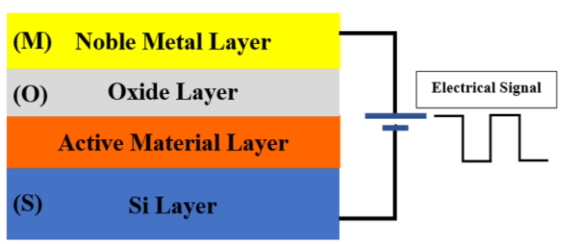

Figure 2: the 2D- YZ view of MOS waveguide that appears in the middle of two Si- arms.

The MOS waveguide consists of four layers have different heights; from bottom to top as follows: a) Si layer of 340 nm, b) active material (ITO) layer of 20 nm, c) oxide layer of 20 nm and finally d) noble metal (silver) layer of 100 nm.

Some of the design parameters from previous researches were incorporated as primary elements in our design, with modifications and suggestions made for the remaining parameters.

Subsequently, an optimization process was carried out to attain the highest efficiency for the device. The careful selection and harmonization of previous design parameters enable a favorable balance between device length, footprint, modulation depth, and energy consumption when compared to the results reported in earlier studies, as will be demonstrated later.

2.2 The Working Principle of Hybrid Plasmonic Electro-Optic Modulator

The length of plasmonic electro-optic modulator is designed to ensure a satisfactory power transfer between the input/output ports. The proposal indicates that the modulator length can be set to an integer (n) of the desired mode wavelength (λ) in the following manner [20-21]:

$$\textbf{Modulator Length}\ (L_M) = n\lambda \tag{6}$$

The modulation process involves modifying the refractive index of the active medium, situated between the layers of the MOS waveguide, through forward biasing of the MOS waveguide using an external electrical potential applied between the noble metal layer (positive) and the Si layer (ground), as illustrated in figure (2). Upon applying bias to the MOS waveguide, the effective index of the optical mode shifts, leading to variations in the modal overlap between neighboring waveguides [22-23].

Previous research studies have examined the impact of the applied electrical potential value on the active ITO material, particularly its index change, and its correlation with the material's dimensions, including the number of ITO layers and the width of each layer. Additionally, investigations have been conducted on different biasing approaches, such as mono biasing (positive and ground) or dual biasing (positive and negative). Numerous previous works, listed in the references, have experimentally validated the optical properties of ITO materials [24–25].

2.3 Testing the Performance of Hybrid Plasmonic Electro-Optic Modulator

The proposed modulator in this work is mainly realized via Metal Oxide Semiconductor (MOS) waveguide. An ITO layer which sandwiched between the MOS waveguide layers is responsible for the modulation mechanism and govern the propagation at the telecommunication range via its peculiar plasmonic characteristics [26-27]. These words can be cleared after showing the electric field intensity distribution proposed in figure (3) which distinguish between the device before and after adding its main unit (MOS waveguide).

As shown in figure (3-a), the absence of the MOS waveguide causes the input electromagnetic mode to be trapped inside the input waveguide, resulting in no output. However, after adding the control unit, the structure offers two options: either blocking the input in its OFF state or allowing the input to pass to the output port in its ON state, as depicted in part (b) of figure (3).

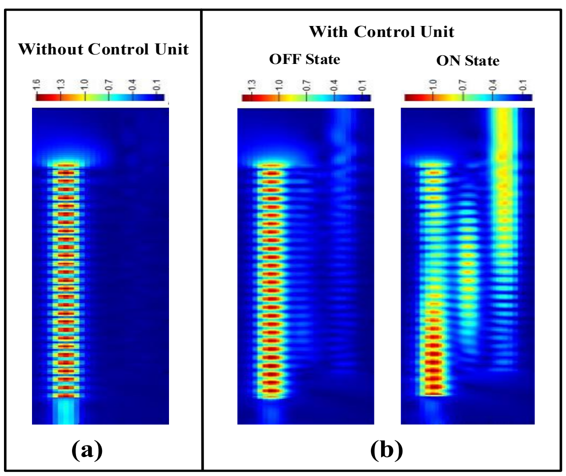

Figure 3: after exciting the device with a transverse magnetic (TM) polarized mode at the input port; the electric field intensity distribution of plasmonic modulator over XY plane is presented as: a) before adding the control unit and b) after adding the control unit when b-1) the modulator is in its ON state and b-2) the modulator is in its OFF state. The test is applied at telecommunication wavelength (1550 nm) and using suggested design parameters, which listed in table (1), has been collected from previous researches with some new considerations and modifications.

Based on electronic principles, the MOS waveguide can function as a capacitor, as depicted in figure (4). Applying a forward bias to this capacitor, which involves a high voltage at the noble metal-electrode and a low voltage at the Si-electrode, initiates a charging process. This results in the trapping of electromagnetic waves within the waveguide, effectively blocking their transmission to the output port. While in the absence of a voltage source, the capacitor is discharging and hence passes the electromagnetic waves to the output port.

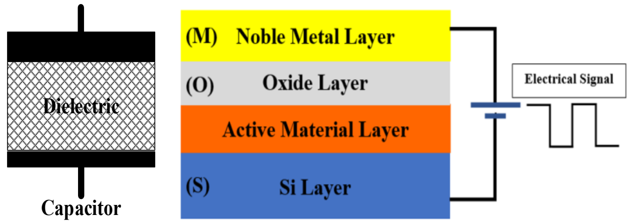

Figure 4: the 2D- YZ view of MOS waveguide that appears in the middle of two Si- arms.

At the process of charging, an accumulation layer has been created at the interface between the oxide and ITO layers. this rises an alteration in the index of dominant optical mode. The design parameters and optical properties of ITO layer that used in this work are collected from previous works [28-29] as following: the refractive index of ITO layer is 1.96+i0.002 when the biasing sets to zero volt and this case is called OFF state while the refractive index of ITO layer changes to 0.471+i0.643 in the ON state if the biasing sets to 4 volts, these optical properties is obtained when the thickness of ITO equals 20 nm.

The performance of plasmonic modulator is affected by its design parameters such as the dimensions of three waveguides, the gap between three waveguides, and the used materials. An optimization can be applied to enhance the modulator' performance.

The main points have taken in considerations through applying the optimization process are: a) decreasing the device' dimensions in order to decreasing the footprint. b) increasing the modulation depth; in other hand, increasing the transmission at ON state and simultaneously decreasing the transmission at OFF state for the modulated signal at output port. c) increasing the modulator' speed and decreasing its consumed energy.

To facility the simulation steps, we start the simulation by using some design parameters taken from previous researches [29] beside suggested parameter concerns this work, then an optimization can be applied to enhance the modulator' performance. All of the used design parameters are listed in table (1).

Table 1: The suggested design parameters for plasmonic modulator.

Modulator length (L_M)	Changes from (1- to -11) µm
MOS waveguide	width (275 nm) and height related to the used layers
Each Si- arm	width (400 nm) and height (340 nm)
Measuring distance (D)	200 nm
Layers of MOS waveguide	Si layer with height equal to height of two Si- arms
	ITO layer with height of 20 nm
	SiO_2 layer with height of 50 nm
	Silver layer with height of 100 nm

The performance of proposed modulator was initially tested by means of the transmission at ON/OFF states and the modulation depth. By using data presented in table (1), the obtained results are shown in figure (5) and they validate the modulation mechanism also present good measurements at modulator length (L_M) of 6 µm.

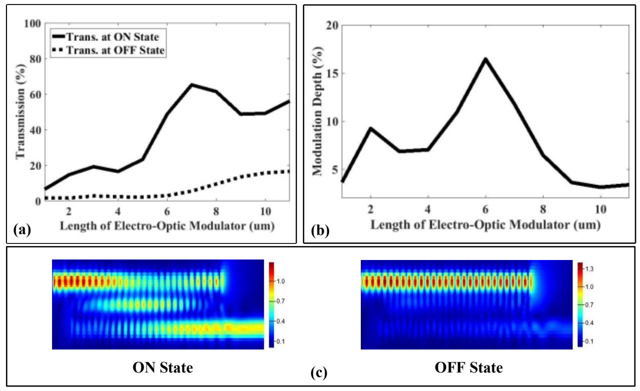

Figure 5: showcases the plasmonic modulator's performance in both ON and OFF states, demonstrated by: a) the transmission as a function of the modulator's length and b) the distribution of electric field intensity. The measurements were taken at the telecommunication wavelength (1550 nm) with a 50 nm height for the SiO2 layer. The electric field intensity distribution across the plasmonic modulator serves as validation for the modulation process.

We start the optimization process by changing the height of SiO_2 layer and again test the modulator' performance as illustrated in figure (6). After displaying and analyzing the obtained results, it was found that there is a better harmony between the dimensions of modulator in the case of choosing the oxide height with a value of 20 nm. This harmony appeared clearly in the performance of the proposed modulator, as shown in Figure 6, especially when the length of electro-optic modulator is 6 µm

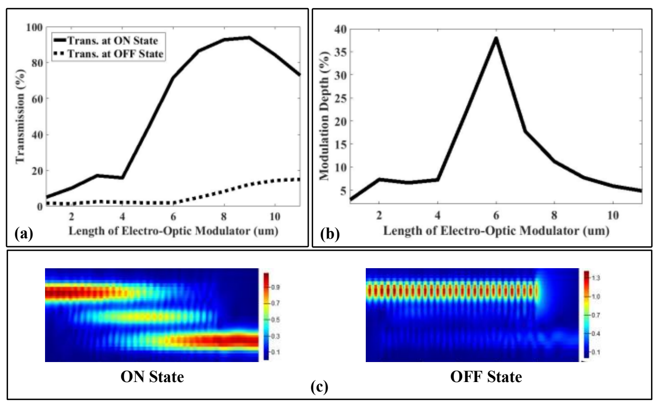

Figure 6: exhibits the plasmonic modulator's performance in both ON and OFF states, represented by: a) the transmission as a function of the modulator's length, and b) the distribution of electric field intensity. The measurements were conducted at the telecommunication wavelength (1550 nm) with a SiO2 layer height of 20 nm. The validation of the modulation process is demonstrated through the electric field intensity distribution across the plasmonic modulator.

After making several attempts in the optimization process to reach the best oxide height for a better performance, We discovered that the device achieves satisfactory efficiency when the height of SiO_2 layer is 20 nm, also, these results remains fairly constant when changing the height of SiO_2 layer by ($\pm \boldsymbol{4\ nm}$) and it is a good fault tolerance during the manufacturing process as cleared in figure (7). And since we seek to choose the highest modulation depth (h) with the least modulator length (L_M), the choice fell on the following design' elements: ($L_M = 6\ \mu m$) and ($h = 20\ nm$)

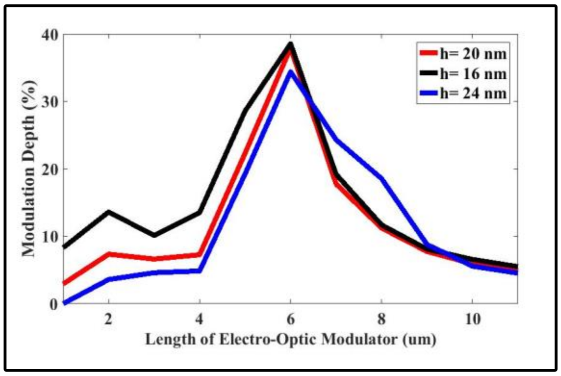

Figure 7: presents a comparison of the plasmonic modulator's performance by plotting its modulation depth as a function of the modulator's length. The results illustrate the achieved gains when varying the height of the SiO2 layer (h) from 50 nm to 20 nm.

Other important parameters for testing the performance of proposed modulator are its energy consumption and bandwidth which related to the RC- delay time; The capacitance of MOS waveguide, that determined by equation (5), is what mainly controls these parameters. An eminent goal is to design more compact structure with minuscular RC-delay constants across femto- joule per bit energy consumption, while maintaining the high modulation depth of modulator at the same time.

The estimated capacitance for the proposed modulator is computed at its OFF state which is the state of charging (trapping the EM wave inside MOS waveguide), the ITO material acts as a quasi-metal so the dielectric is only the SiO_2 material with $\varepsilon_{\text{Dielectric}}$ of 3.9, W of 275 nm and t of (20-40) nm. According to equation (5), the estimated capacitance is (1.4-2.847) fF; and hence the modulation bandwidth is determined by using equation (3) with $R = 500\ \Omega$, and the consumed energy through modulation process is determined by equation (4) with $V = 4\ volts$. The estimated values for modulation B.W and energy consumption are (0.7-1.405) THz and (11.384-22.7) fJ/bit, respectively. Also, the structure achieved more compact footprint compared to the previous works that used the same techniques; the estimated footprint for the proposed modulator does not exceed $(11\ \mu m^2)$ as a maximum.

2.4 Validation

One of the most important parts of the research process is to compare the obtained results with what preceded it, to find out whether the improvement took place and the previous defects disappeared or not. The results obtained at the telecommunication wavelength (1550 nm) are utilized for validation, comparing them with the outcomes from various previous works that employed similar technology. The validation process and corresponding results are presented in table (2).

Table 2: a validation between the present work and previous ones at the telecommunication wavelength (1550 nm)

	Reference [33]	Reference [32]	Reference [31]	Reference [30]	Present work
Modulator Length (µm)	3	5.53	-	-	6
Modulation Depth (dB)	7.86	-	20	10	38
Modulation Speed	40 MHz	363 (GHz)	0.1 (GHz)	30 (GHz)	(0.7 - 1.405) THz
Energy consumption per bit (fJ)	-	14.8	8×10^3	800	11.384 - 22.7
Foot print (μm^2)	-	-	200	6.4×10^3	11

Conclusion

Small footprint, low power consumption, and high modulation depth are key requirements for the advancement of next-generation electro-optic modulators. This work presents a high-speed electro-optic hybrid plasmonic modulator and examines its crucial parameters. Furthermore, a validation with previous works has been conducted.

By analyzing the obtained results and comparing them with those from previous research, the efficiency of the device proposed in this study was demonstrated.

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