Optical Modulator using Ultra-Thin Silicon Waveguide in SOI Hybrid Technology

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Short Report

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Optical Modulator using Ultra-Thin Silicon Waveguide in SOI Hybrid technology

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Conflict of interest

The authors declare that they have no conflict of interest.

Author Contributions

A..b. Ayoub conceived the basic idea and validated the concept of operation through computer-aided simulations. M.A. Swillam supervised the entire project. All the authors contributed to the general discussion and revision of the manuscript.

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Abstract. We propose a detailed study of an on-chip optical modulator using a non-conventional silicon-based platform. This platform is based on the optimum design of ultra-thin silicon on insulator (SOI) waveguide. This platform is characterized by low field confinement inside the core waveguide and high sensitivity to the cladding index. Accordingly, it lends itself to a wide range of applications, such as sensing and optical modulation. By employing this waveguide into the Mach-Zehnder interferometer (MZI) configuration, an efficient optical modulator is reported using an organic polymer as an active material for the electro-optic effect. An extinction ratio of more than 20 dB is achieved with energy per bit of 13.21 fJ/bit for 0.5 V applied voltage. This studied platform shows promising and adequate performance for modulation applications. It is cheap and easy to fabricate.

Keywords: interference, modulation, photonic structures, Mach-Zehnder Interferometer, ultra-thin.

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1 INTRODUCTION

Silicon Photonics is a CMOS-compatible platform technology that is power-efficient while approaching operating speed comparable to that of light [1]. Aiming at high-bandwidth systems with high operating speed, electronic and photonic circuits were integrated as in data-communication systems, which resulted in systems with outstanding speed rates and lower power losses. Besides, photonic integrated circuits have been employed in different applications, including optical modulation, and sensing [1-3].

Optical modulators play a vital role in optoelectronic systems. Thanks to these components, electronic signals are converted to optical signals that propagate using optical waveguides [1]. Commonly, optical modulation is done either through an Electro-optic effect (i.e., Pockels, Kerr) or a thermo-optic effect [1]. While silicon lacks electro-optic effects, it has a high thermo-optical property at low speed (i.e., it cannot be employed in high-speed communication systems) [4].

Recently, various photonic based modulating structures have been demonstrated [5, 6]. A silicon-organic hybrid modulator was proposed [5] that operates at frequencies up to 100 GHz and beyond so that it can be used in electronic-photonic processing at high speed. Despite its large length of 500 μm, phase efficiency of 11 V.mm, and a capacitance per length of about 100 fF/mm with a parasitic resistance of few Giga-ohms. A high-speed silicon Mach-Zehnder modulator (MZM) with a low insertion loss of 1.9 dB was demonstrated [6]. Phase efficiency of less than 2 V·cm was achieved despite an arm length of 750 μm. High-performance modulation with an extinction ratio of 7.5 dB was delivered at 50 Gbps at the expense of an additional optical loss.

From the previous examples, it is observed that achieving a high-performance photonic structure is considered a tradeoff between the size, loss, and fabrication complexity of photonics modulators. Most of the current silicon photonics-based modulators are based on few hundreds of nanometer waveguide width that requires electron beam lithography technology (EBL) for fabricating these waveguides. Alternatively, it can be fabricated with a high-quality mask with a submicron dimension. However, this mask is also expensive and requires specialized technology to be produced.

Therefore, the need for a new platform for designing photonic structures with standard fabrication technology is necessary. With the proposed platform, standard and straightforward fabrication technology can be employed to fabricate structures with dimensions of more than 1.0 microns. Allowing for standard technology for mask preparation and effectively alleviate the need for EBL technology. On the other hand, the suggested platform also has a unique feature for being more sensitive than other larger waveguide platforms such as ridge configuration, as will be explained through the manuscript.

The paper is organized as follows: section (2) describes the properties of the proposed platform, section (3) studies the photonic modulator based on the proposed platform, and finally, section (4) concludes the paper.

2 ULTRA THIN WAVEGUIDE PROPERTIES

Several studies previously proposed a similar platform to the one proposed in this work [7-13]. The proposed platform is based on an ultra-thin SOI that supports the fundamental mode, as would be seen in a conventional SOI (t=220 nm, W=400nm). The silicon waveguide is shown in Fig. 1, it has a thin thickness (t) of only 50 nm.

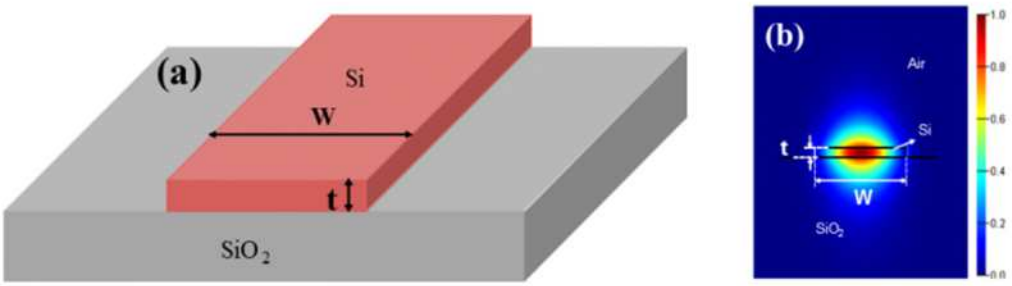

Fig. 1 SOI ultra-thin waveguide structure. (a) Schematic for the physical dimensions of the ultra-thin waveguide. (b) Mode profile for the ultra-thin SOI.

The ultra-thin SOI technology supports only the TE mode owing to the small thickness. TE mode is defined by the mode whose major component is along the longer dimension in the plane of incidence (major electric field component along "W"). Due to the small thickness, the TE mode has a low confinement factor inside the waveguide as shown in Fig. 1(b) [10-13]. The mode profile in Fig. 1(b) was calculated using the mode solver of Lumerical [14]. On the other hand, TM mode (i.e., major electric field component along "t") can be supported by expanding the thickness (t) of the waveguide as in a conventional waveguide that has a thickness of 220nm. However, if t=50nm, regardless of (W), TM mode will not be supported by the waveguide.

In the SOI geometry, it is assumed that the surrounding is air, while the substrate is silicon dioxide (SiO_2) with a thickness of 1 μm to avoid leakage to the silicon wafer. Substrate leakage loss attenuation is given by the following equation (1) [15]:

$$\alpha_{leak} = e^{-2\left(\sqrt{n_{eff}^2 - n_0^2}\right)k_0 A} \quad (1)$$

where $\boldsymbol{k_0} = \frac{2\pi}{\lambda_0}$ is the free space wavenumber, $\boldsymbol{n_{eff}}$ is the effective index of the mode, $\boldsymbol{n_0}$ is the effective index of the oxide layer, and $\boldsymbol{A}$ is the thickness of the oxide, in which for the given parameters ($\boldsymbol{\lambda_0}$=1550nm, $\boldsymbol{n_{eff}}$=1.55, $\boldsymbol{n_0}$=1.45, $\boldsymbol{A}$=1 μm), $\boldsymbol{\alpha_{leak}} = \boldsymbol{0.011}$. Such value can be further suppressed by increasing the thickness ($\boldsymbol{A}$) to 2 – 3 μm.

Modal analysis was done by varying the dimensions of the waveguide cross-section using mode solver of Lumerical [14]. The effect of changing the width of the waveguide "W" on the effective refractive index of the structure while keeping t=50 nm is shown in Fig. 2. Only the first fundamental mode is supported with 700nm < W < 2μm, no modes are supported when W< 700 nm. On the other hand, multi-modes are supported given W>2 μm. Throughout the paper, silicon waveguide with parameters (t=50 nm, W=2 μm) will be used. This waveguide can be fabricated using the standard fabrication process for the conventional waveguide. The fabrication steps are performed as follows: (1) performing a partial etching on silicon on insulator platform to get the required thickness (i.e., t=50 nm), (2) then performing mask lithography, (3) development of the wafer, (4) performing the dry etching process to etch the unneeded Si layer, and (5) finally remove the etchant to reach the final structure. Fabrication tolerance will not affect the overall performance, as seen in Fig. 2 in which the n_{eff} is not oscillating as a function of the width, the fact that compensates the fabrication tolerances due to large width.

During the computational analysis, the MZI has an arm length of 350 μm and a bending radius of 80 μm. The propagation loss is calculated for the waveguide to know the limitations on the arm length. A propagation loss of 0.024 dB/cm is considered an acceptable value for the design of long-arm modulators. However, additional terms can include the bending loss of the MZI, which is in the range of 2.5 dB/cm at a bending radius of 80 μm. Adding a surface roughness of 3 dB/cm can result in a total loss of around 0.2 dB for an arm length of 350 μm. In the following section, an ultra-thin MZI optical modulator is discussed in detail. A comparison with other modulation systems is also performed.

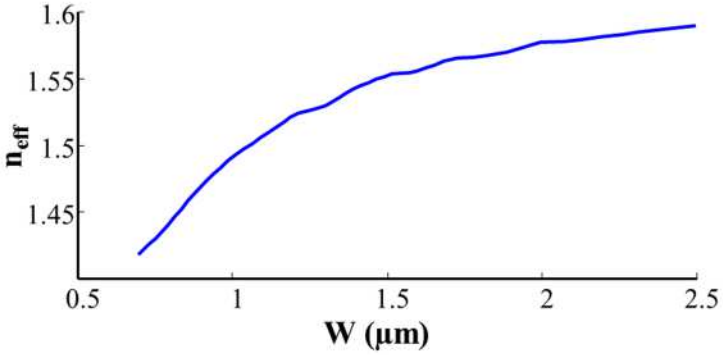

Fig. 2 The effect of changing the waveguide width on the effective index. The substrate is assumed to be SiO_2 with air as the surrounding.

3 ULTRA THIN WAVEGUIDE BASED PHOTONIC MODULATOR

3.1 MZI based Photonic Modulator

Electromagnetic simulations are performed using the commercial Beam Propagation Method (BPM) [16]. Assuming polymer with the Pockels electro-optic effect, refractive index change is governed by equation (2) [17]:

$$\Delta n = \frac{1}{2} n_0^3 r_{33} \frac{V_a}{t_p} \quad (2)$$

where n_o is the polymer refractive index at zero applied voltage and has a value of 1.6, V_a is the applied voltage, t_p is the thickness of the polymer, r_{33} represent the electro-optic effect and has a value of 310 pm/V. This polymer can be retrieved by a 1:1 mixture between (C28H21F3N4OS, molecular weight 518.6) and (C32H28F3N4O, molecular weight 541.6), as discussed in Ref. 18. Having $t_p = 200\ nm$, resulted in a calculated metal absorption loss of 24dB/cm, yielding a total metal absorption loss of 0.84 dB for an arm length of 350 µm. "On" state is reached when applying voltage V_a = 2V through the metal electrodes resulting in a refractive index change of $\Delta n = 6.35 * 10^{-3}$, as given by equation (2).

The schematic of the optical modulator design is shown in Fig. 3(a). As discussed in the previous section, the TE mode is weakly confined in the ultra-thin waveguide, allowing for better penetration into the polymer, as shown in Fig. 3(b). Field distribution is calculated using the mode solver of Lumerical [14]. High field penetration into the polymer allows for a higher extinction ratio at significantly shorter arm length as compared to conventional SOI systems.

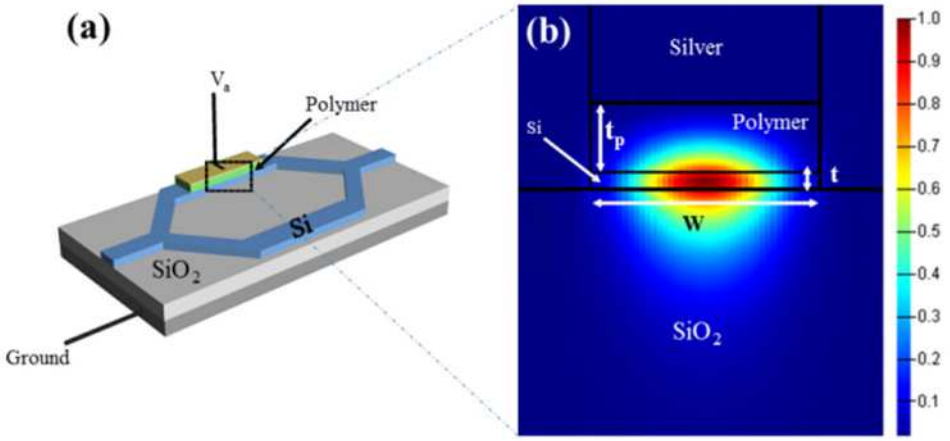

Fig. 3 MZI photonic modulator. (a) Schematic for the ultra-thin SOI modulator. (b) mode profile inside the polymer, it shows the strong interaction between the optical mode and the polymer.

3.2 Modulator Results

As mentioned in the previous section, during the computational analysis, the arm length was designed to be 350 µm with a bending radius of 80 µm, with a polymer thickness "$\boldsymbol{t_p}$"of 200 nm yielding an acceptable capacitance (C) value of 79.27 Ff without dramatically suppressing the performance [12]. Assuming bit-rate (R_{bit}) of 0.1Tbit/sec, the power consumption for a return to zero (RTZ) can be calculated using equation (3) [19]:

$$\boldsymbol{P = \frac{1}{2} R_{bit} C V_a^2} \quad (3)$$

Assuming applied voltage $\boldsymbol{V_a}$**=2V**, $\boldsymbol{P} = 0.0158$W. Hence, ($\boldsymbol{E_{bit} = \frac{1}{2} C V_a^2}$) equals 158 fJ/bit [12]. The half-wave voltage $\boldsymbol{V_\pi}$ is calculated using equation (4):

$$\boldsymbol{V_\pi = \frac{\lambda_0 t_p}{n_0^3 r_{33} \zeta}} \quad (4)$$

,where $\boldsymbol{\zeta}$ is the arm length, Given the above parameters, $\boldsymbol{V_\pi} = 0.697$ V and $\boldsymbol{V_\pi \zeta} = 2.44 * 10 - 2$ V. cm. At an $\boldsymbol{\lambda_0 = 1550\ nm}$, the extinction ratio (ER) equals 11.3 dB which is given by $\boldsymbol{ER = 10\ log \frac{P_{on}}{P_{off}}}$; where $\boldsymbol{P_{on}}$, $\boldsymbol{P_{off}}$ is the power in the "On" and "Off" state, respectively.

Fig. 4 shows the effect of changing the polymer thickness on the performance while setting the field $\frac{V_a}{t_p}$ to a certain constant (i.e., Δn has a constant value). A constant field is conserved by varying the V_a for different t_p. By doing this analysis, a compromise between ER and E_{bit} is achieved.

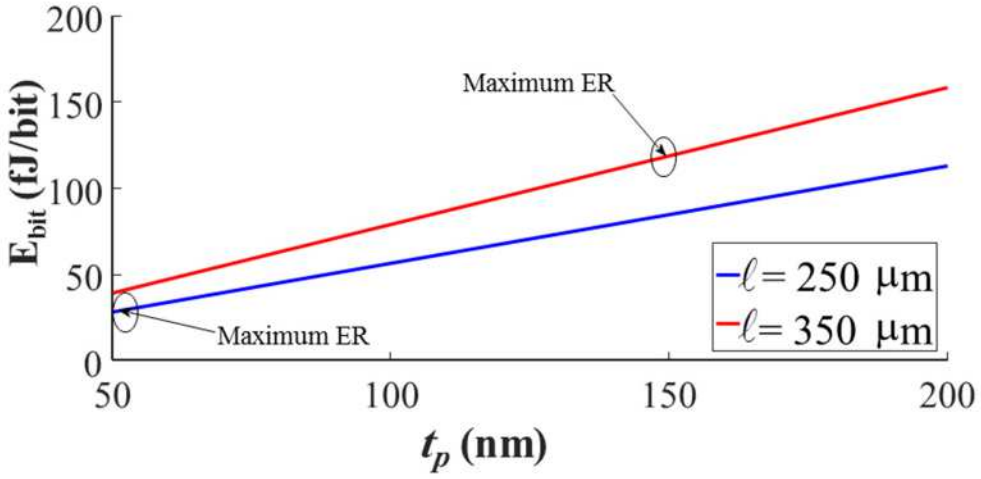

Fig. 4 E_{bit} versus polymer thickness (t_p) for different MZI arm length

In addition, Fig. 4 shows the E_{bit} as a function of the t_p for constant Δn of $6.35*10^{-3}$ at different ζ. The arrows show the positions of the maximum extinction ratio (ER) for each ζ. For a ζ of 250 μm, a maximum ER of 25.14 dB occurs for $t_p$of 50 nm while for a ζ of 350 μm, a maximum ER of 23.02 occurs for t_p of 150 nm. The previous study shows that for maintaining a maximum ER, t_p has to be increased with increasing ζ. On the other side, by changing t_p and ζ, V_π will change in which V_π is 0.25V at (ζ =250 μm, t_p= 50 nm) while it is 0.52V at (ζ =350 μm, t_p= 150 nm) which reflects the trade-off between E_{bit}, and ER, and V_π and the need to have an optimized design to compromise between these performance metrics.

Table 1 shows the effect of applying different voltages and using different channel lengths on the performance of the modulator in terms of the E_{bit}, ER, and $V_\pi\zeta$ metrics at $\lambda_0 = 1550\,nm$. As shown in the table, modulator performance varies based on the design parameters selected for the optical design. From table 1, it could be demonstrated that a polymer having a thickness of 150 nm at an applied voltage of 0.5 V represents the best compromise between ER and E_{bit}, and ζ at a wavelength of 1550 nm with an ER = 20.36 dB, E_{bit} =13.21 fJ/bit, and ζ = 350 μm.

Table 1. Different modulators design performance in terms of E_{bit}, ER, and $\boldsymbol{V_\pi \zeta}$ at $\boldsymbol{\lambda_0 = 1550\, nm}$.

Applied Voltage (V)	Polymer Thickness $\boldsymbol{t_p}$ (nm)	Energy per bit (E_{bit}) (fJ/bit)	(ER) (dB)	Channel Length ($\boldsymbol{\zeta}$) (μm)	$\boldsymbol{V_\pi \zeta}$ (V.cm)
2V	150	151.2	16.8	250	$1.83*10^{-2}$
	150	211.7	20.1	350	$1.83*10^{-2}$
1.5V	150	84.96	12.97	250	$1.83*10^{-2}$
	150	118.94	23.02	350	$1.83*10^{-2}$
1V	150	37.76	6.27	250	$1.83*10^{-2}$
	150	52.86	22.44	350	$1.83*10^{-2}$
0.5V	150	9.44	2.93	250	$1.83*10^{-2}$
	150	13.21	20.36	350	$1.83*10^{-2}$

A similar design was demonstrated in [7] in which an MZI based modulator with ultra-thin silicon waveguide was fabricated. Although the design looks identical to the proposed design here, the performance of both models is quite different. In [7], the MZI-based modulator has a propagation loss of 4dB/cm compared to 0.024 dB/cm in our paper. Owing to the high electro-optic coefficient of the polymer used here, we believe the ER will surpass the achievable ER in [7] (i.e., r_{33}=310 pm/v in the proposed work, r_{33}=70 pm/v in [7]). Besides, we reach E_{bit} as low as 13.21 fJ/bit compared to 30.18 fJ/bit. Table 2 shows the performance of the proposed MZI based modulator as compared to silicon-based modulators previously proposed with different structures. As shown, the proposed model is considered a good compromise between each of ER and E_{bit}. Assuming low doping concentration, the resistivity of silicon is around 10 Ohm.m. Whereas the waveguide has a thickness of 50 nm, and the area equals 350 μm x 2 μm. The resistance is calculated to be 714 ohms. Hence, the speed of the modulator can be estimated to be 17.66 GHz. The maximum modulation bandwidth (f) that can be achieved is inversely proportional to the change in the refractive index and is given by equation (5) [20]:

$$(\boldsymbol{f} * \boldsymbol{\zeta})_{max} = \frac{\boldsymbol{c}}{\boldsymbol{4\Delta n}} \quad (\mathbf{5})$$

where c is the speed of light in air. From this equation, for $\Delta n = 6.35 * 10^{-3}$, and arm length ($\zeta$) of 350 μm, $f_{max} = 3.37 * 10^{13}$ Hz.

Table 2. Comparison between the proposed structure and the previously proposed silicon-based modulators.

Modulation principle	Modulator Structure	Extinction Ratio (ER) (dB)	Energy per bit (E_{bit}) (fJ/bit)
Electro-Optic [7]	MZI	--	30.18 @V_a=2V
Carrier Depletion [21]	MZI	3.8	147,000
Carrier Injection [22]	MZI	10	5,000
Carrier Injection [23]	Ring	7	120
Carrier Depletion [24]	Ring	6.5	50
Electro-refractive (proposed)	MZI	20.36	13.21

The transmitted intensity is plotted in Fig. 5 as a function of wavelength in which high ER is achieved at 1550 nm with E_{bit} =13.21 fJ/bit [12, 13].

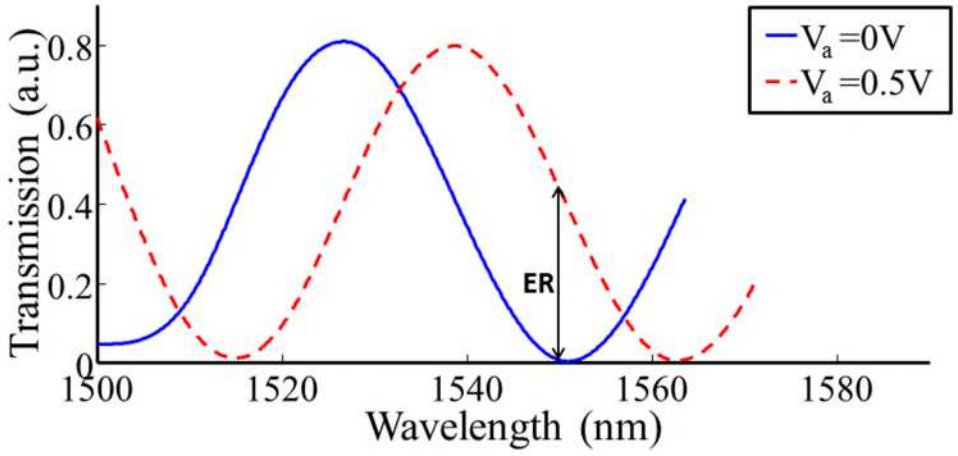

Fig. 5 Transmission versus wavelength in the "On" and "Off" states.

4 CONCLUSION

MZI optical modulator based on the ultra-thin is presented in this paper. An MZI – based modulator is proposed. An extinction ratio of 20.36 dB at 1550 nm with an arm length of 350 µm is reported. With an applied voltage of 0.5V, the low power consumption of 0.0158 W is achieved at high speed rates.

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Biographies

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Mohamed A. Swillam received his Ph.D. from McMaster University, Hamilton, Canada, in 2008. After graduation, he worked as a postdoctoral fellow in the same group. In October 2009, he joined the photonic group and the Institute of Optical Sciences at the University of Toronto as a research fellow. In September 2011, he was appointed as an assistant professor at the Department of Physics, the American University in Cairo (AUC). His research interests include active and passive nanophotonic and plasmonic devices and systems, silicon photonics, metamaterials, and solar cells.

Caption List:

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