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Electro-Optic Slot Waveguide Phase Modulator on the InP Membrane on Silicon Platform

A.A. Kashi¹, J.J.G.M. van der Tol¹, K. Williams¹, W. Yao¹, M. S. Lebby², C. Pecinovsky², and Y. Jiao¹

Abstract— For the first time, we present an electro-optic slot waveguide phase modulator on the InP membrane on Silicon (IMOS) platform. Low-frequency characterization of this modulator shows that it can achieve a $V_\pi L_\pi$ product as low as 4.5 V.mm and an extinction ratio equal to 10.6 dB. The 3-dB optical bandwidth of this modulator is measured to be 10.5 GHz. Here, working principles, design, fabrication, measurements, analysis of the electrical and electro-optic performance and prospects of this modulator are presented.

Index Terms— Optical device fabrication, Optical polymers, Optical modulation, Optical communication, Integrated optics, Electrooptic modulators

I. INTRODUCTION

A high-speed modulator is an essential component for photonic integrated circuits (PICs) to enable high data rate communications. Significant research efforts have been focused on the improvement of the efficiency and bandwidth of the modulators. One promising solution to achieve such a high-speed modulator is to use a slot waveguide filled with electro-optic (EO) polymer [1], which can induce a phase shift in the optical signal when an electric field is applied. This type of modulator is called electro-optic slot waveguide phase modulator. It has been introduced on silicon photonics platforms, known as the silicon-organic hybrid (SOH) modulator.

Recent advances in SOH-modulators have shown the great potential of these devices for very fast, on-off-keying (OOK) at 100 Gbit/s, and energy-efficient, fJ/bit power consumption, phase modulators [2-4]. These modulators can achieve very high modulation efficiencies with low voltage-length products ($V_\pi L_\pi$). The state-of-the-art SOH modulator shows $V_\pi L_\pi$ below 0.1 V.mm using a highly efficient EO polymer [4], which positions it among the most efficient modulators. However, as is depicted in Figure 1, InP, compared to Si, features lower optical loss and higher carrier mobility at the same doping levels [5]. These properties enable InP based devices to achieve higher doping concentration levels to reduce the electrical resistance of the device, while keeping the optical insertion loss

low and mobility high. This can potentially enable larger modulation bandwidth and better modulation efficiency [5]. To elaborate, lower optical insertion loss leads to a higher optical modulation amplitude. On the other hand, electrical resistance of the device is a key component to determine the modulation bandwidth of the device, and if it can be lowered, the modulation bandwidth could be improved.

It is not feasible to utilize traditional substrate based InP [6] to fabricate slot waveguide modulators because of the weak optical confinement. On the contrary, the InP membrane on Silicon (IMOS) [7, 8] is a versatile platform to realize a slot waveguide modulator. The high refractive index contrast in the IMOS platform leads to high mode confinement and reduced dimensions of components. This enables slot waveguides in the IMOS platform with similar dimensions to those in SOH.

With this platform, apart from utilizing the superior performance of InP materials, both passive and active components, such as lasers, can be fabricated in one optical layer without hybrid assembly.

In this paper, the working principle of the slot waveguide modulators will be explained, and the design and fabrication of this device will be described. Next, both the low and the high-frequency characterization of a fabricated device will be reported. Finally, the electrical and electro-optical performance will be analyzed, leading to predictions on the achievable performance.

Fig. 1. (Right Y-axis) Mobility of InP compare to Si as a function of doping concentration. InP mobility is near 10 times higher in high doping concentrations. (Left Y-axis) Carrier absorption coefficient of InP compare to Si versus doping concentration. The carrier absorption coefficient of InP is nearly half of that of Si.

II. WORKING PRINCIPLE

In Figure 2 the design of the Mach-Zehnder interferometer (MZI) modulator, with slot waveguide phase shifters in the branches, is illustrated. The TE fundamental mode is coupled to the chip with a surface grating coupler [9]. It is split with a symmetric 1x2 Multi-Mode Interferometer (MMI) over the two arms. There the light is converted to the mode of the slot waveguide [10]. These waveguides confine the optical mode primarily in the slot which contains an EO polymer, see Figure 2(c). This leads to a high overlap of the optical mode with the EO polymer.

Fig. 2. (a) Illustration of the MZI modulator where the two arms are made of slot waveguides. Inset shows the magnified view of one of the arms. [11] (b) Cross section of the MZI arm with dimensions. (Note that the rail width applies to both rails.) (c) Electric field distribution of the optical mode over the slot.

These polymers are able to induce a phase shift to the optical mode due to the refractive index change while applying an electric field, according to equation 1[4].

$$\Delta\varphi = 1/2 \cdot r_{33} \cdot n_{EO}^3 \cdot V / w_{slot} \cdot \Gamma_{slot} \cdot L \cdot k_0 \quad (1)$$

Where $k_0 = \frac{2\pi}{\lambda}$ is the optical wavenumber at a vacuum wavelength λ and r_{33} , n_{EO} , V , w_{slot} , L and Γ_{slot} are the electro-optic coefficient of the polymer, effective refractive index of the EO polymer, applied voltage, width of the slot, Length and confinement factor of the optical mode in the slot, respectively.

The confinement factor is also called the field interaction factor. It can be obtained in terms of the vectorial mode fields $\mathcal{E}_0(x, y)$ and $H_0(x, y)$ of the waveguide mode:

$$\Gamma_{slot} = \frac{c\epsilon_0 n_{EO} \iint_{A_{slot}} |\mathcal{E}_{0,x}(x, y)|^2 dx dy}{\iint_{A_{total}} \text{Re}\{\mathcal{E}_{0,x}(x, y) \times H_0^*(x, y)\} e_z dx dy} \quad (2)$$

Where, A_{slot} , A_{total} , c and ϵ_0 are the area of the slot region, the total area where the fields are present, speed of the light in vacuum and the dielectric constant of vacuum, respectively.

In our MZI modulator, the InP slot waveguides are electrically contacted with a highly n-doped (1×10^{18}) InP layer (30 nm thickness) which is connected to contact pads. These pads are placed 2 μm away from the slot waveguide, to prevent unwanted losses due to interaction of the optical mode with the metals. On the other hand, this distance is designed to give a reasonably low electrical resistance.

III. DESIGN

In this section the design of the first generation of the electro-optic slot waveguide phase modulator will be discussed. In this design, performance optimization is performed with considerations from fabrication constraints and measurement simplicity. This approach led to a design with parameters which are different from the most optimum case. Later in section VI, the most optimum design will be presented to illustrate the full potential of the device.

The optical properties of the MZI are optimized with Finite-Difference Eigenmode (FDE) [12] and Time-Domain (FDTD) [13] solvers to reach low mode loss and high confinement of the light in the slot.

Figure 3 presents the results for the fundamental TE mode in a 100 nm wide slot.

Although the best rail width for a 100 nm slot in terms of low optical mode loss and high confinement factor is 250 nm, 300 nm has been chosen to reduce the effects of fabrication imperfections like the sidewall roughness and dimension inaccuracies. The obtained optical mode loss is then 0.05 dB/m, with the confinement factor (Γ_{slot}) equal to 28.5%.

Fig. 3. Relation of the Loss (left Y-axis) and confinement (right Y-axis) factor versus rail width for a 100 nm slot width. Please consider in this simulation, doping and sidewall roughness are not considered in calculation of the propagation loss.

It is expected that the EO polymer used in this work has a bulk electro-optic coefficient (r_{33}) of around 110 pm/V. If the maximum voltage is limited to 1 V, to be compatible with CMOS voltage constraints, we can obtain the arm length required for a π phase shift in our MZM.

From equation 1 it is found that, a minimum electrode length of 500 μm is needed to achieve π phase shift. These long electrodes are comparable to the wavelength of the radio

frequency (RF) electrical signal required for driving this modulator. Therefore, a traveling-wave electrode design was considered to reduce the effects of RF reflection, loss and velocity mismatch. Electromagnetic field simulation software [14] was used to design these traveling-wave electrodes. Three parameters mainly influenced the electrode performance: electrode height, electrode width and distance of the electrode to the center of the slot, see Figure 2(b).

TABLE I
PARAMETERS OBTAINED FOR THE FIRST DESIGN OF TL.

Electrode width	Electrode height	Electrode distance	Slot width	Rail width	Doping concentration of the slab
80 μm	500 nm	2 μm	100 nm	300 nm	1×10^{18}

The performance of the device is the consequence of these three parameters together. In Table I, a set of parameters is reported to satisfy the desired RF properties for the first generation of the transmission line (TL). In Figure 4(a), the characteristic impedance (Z_C) is shown to be around 20 Ohm for the frequency range between 1 to 80 GHz. This Z_C is not ideal for the impedance matching of the TL with the load and the source impedance, which is 50 Ohm. Figure 4(b) shows the RF loss in this frequency range. RF loss at the maximum (80 GHz) reaches 5.1 dB/mm, which is acceptable. In Figure 4(c), the effective refractive index of the RF signal is indicated. In order to reduce velocity mismatch, which limits the bandwidth, it is demanded to have a match between the electrical phase and optical group velocities. This imposes that both the effective refractive index of the RF and the effective group index of optical mode to be as close as possible. In our designed TL $n_{RF} = 3.5$ at 80 GHz which is close to $n_{TE} \sim 3.6$. Figure 4(d) illustrates the S_{21} and S_{11} component from the transfer matrix of the TL. Due to simulation time costs, it is not possible to simulate the whole 500 μm long electrode. Therefore, a device with a 100 μm long electrode was simulated and then its scattering parameters are cascaded [15] to describe the desired modulator arm length. The 6-dB electrical modulation bandwidth can be expected to be much higher than 80 GHz for a 500 μm electrode length. S_{11} shows that there is a reflection in the input of the TL. This reflection is due to the impedance mismatch of the line and the RF source, which is 50 Ohm.

Fig. 4. (a) Optimized Z_C of the TL versus frequency of the RF signal. (b) RF loss versus frequency of the RF signal. (c) RF refractive index versus frequency. (d) S_{11} and S_{21} component of the transfer matrix of the TL.

IV. FABRICATION

The MZI structures are patterned using electron beam lithography (EBL). Fabrication was done on an InP membrane bonded to a silicon substrate (IMOS) with BCB polymer [7, 8]. The thickness of the InP membrane is 300 nm. The fabrication involves four EBL exposures. The first exposure is to define the markers of the pattern for alignment purposes. The markers are etched in the semiconductor with an etch depth of 270 nm. In the second exposure, both waveguides and focusing grating couplers are defined in electron beam resist (ZEP) and subsequently etched in the hard mask (SiN) and finally into the semiconductor (The etch depth is again 270 nm), see Figure 5(a). At the third exposure, the 30 nm of the semiconductor remaining is removed from the slot areas and around the metal electrodes, to electrically isolate the structure, see Figure 5(b). The last exposure is to define the metal contacts, which consists of 30 nm Ni / 50 nm Ge / 250 nm Au (Figure 5(c)).

Fig. 5. Fabrication steps. (a) Second exposure. (b) Third Exposure. (c) Forth exposure.

In Figure 6(a), a microscopic image of the fabricated chip is shown, while in the inset (Figure 6(b)), the magnified SEM image of the slot is depicted. The last step after fabrication is to spin coat a layer of EO polymer on top of the sample. Figure 6(c) shows that the EO polymer fills the narrow slot without any voids.

Lightwave Logic Inc provides The EO polymer used in this work. According to the specification, bulk r_{33} coefficient of this EO polymer is equal to 110 pm/V, and the refractive index is around 1.7. While there are other EO polymer materials with higher EO coefficients [16], this material features very high stability even without a cladding layer. In fact, the measurements on this EO polymer have been done 7 months after fabrication (due to lab closure related to a pandemic). This illustrates the chemical stability of the polymer.

V. CHARACTERIZATION

A. Optical Characterization

In order to calculate the effective group index of the fundamental TE mode in the slot and the slot propagation loss,

while the EO polymer filled the slot, an asymmetric MZM with different slot arm lengths has been fabricated and measured. [17,18]

The effective group index obtained for the slot is around 3.64, and propagation loss in the slot is measured to be around 50 dB/cm for a 100 nm slot width, while the propagation loss for the straight rib waveguide is around 15 dB/cm. Despite the fact that in the introduction section it is stated the optical propagation loss in the slot could be lower than SOH-modulator, it is slightly higher than the state-of-the-art value [19], which is due to the different design parameters and particularly slot sidewall roughness. Further fabrication optimization has to be taken in order to reduce the sidewall roughness.

Fig. 6. (a) Fabricated symmetric MZI modulator on IMOS platform. (b) Magnified view of the inset showing the slot (top view). (c) FIB cross section cut of the dotted line to check the adhesion properties of the EO polymer to InP surface. The dark gray color is EO polymer. It can be seen that EO polymer completely filled the narrow slot without leaving any voids. (side view) Please notice picture (c) is taken with 52-degrees tilting angle respect to the axis vertical to the surface and the sidewall angles of the slot waveguide are exaggerated. Additionally, this FIB picture is taken from a test sample and sidewall angles are not the ones for the real MZM sample.

In Figure 7, the optical transmission spectrum of the asymmetric MZM is shown with the corresponding spectrum from the theoretical model.

A. Low-Frequency Electrical Characterization

The EO polymer needs to be poled in order to obtain the electro-optic properties. Poling is a process in which polymeric chains are aligned in the direction of the applied electric field.

This process includes raising the temperature until the glass transition temperature ($T_g = 155^\circ\text{C}$) of the polymer and cool down slowly with an electric field applied.

After the EO polymer is poled, it can induce a phase shift if an electric field is applied.

Fig. 7. The measured transmission spectrum (blue line) of an asymmetric MZM with its corresponding theoretical spectrum (red line) to obtain the effective group index and optical propagation loss of the fundamental TE mode. Please notice, in this measurement the slot is filled with the EO polymer.

Fig. 8. Optical output power versus bias voltage and corresponding V_π .

Due to charge screening in the EO polymers, it is not possible to characterize the MZI modulator performance in the DC regime. Therefore, a kHz-frequency measurement is used instead. In this measurement, a signal with a triangular waveform is applied to the signal electrode of the GSG electrode (see Figure 6(a)), while the optical signal is passing through the slot. The output optical signal is sent to a photodiode, and an oscilloscope reads the photodiode signal versus time. In Figure 8, the applied voltage signal and the optical output signal are depicted. It can be inferred that V_π is around 9 V for this 500 μm long device. The maximum extinction ratio at V_π is 10.6 dB. Furthermore, from equation 1 the corresponding r_{33} is around 12.5 pm/V . This r_{33} coefficient is lower than specified by Lightwave Logic in bulk form, and with further experimental optimization, the coefficient is expected to be higher. On the other hand, this is a known behavior of the EO polymers when applied inside a narrow opening [1]. It is reported that the r_{33} value of an EO polymer, when applied inside a narrow slot of 100 nm, can be reduced a lot due to the surface effects [1]. However, a series of experiments should be conducted to study the EO polymer's behavior better when applied in the slot

B. High-Frequency Electrical Characterization

The electrical performance of the designed TL is further investigated with a high-frequency electrical measurement. Figure 9 illustrates the device under test driven by an ideal RF source. Transmission and reflection of the RF electrical signal are recorded with a vector network analyzer (VNA).

Figure 10 shows the S_{21} and S_{11} component of the obtained scattering matrix. S_{11} and S_{21} components correspond to the reflection and transmission coefficients of the TL, respectively.

S_{11} is well below -10 dB, which shows the low reflection at the input of the TL. The 6-dB electrical bandwidth of the device is determined by S_{21} and is beyond the frequency limit of our equipment range, which is 67 GHz.

Fig. 9. Pure electrical measurement setup.

Fig. 10. S-parameters of the pure electrical measurement of the fabricated MZI modulator.

C. High-Frequency Electro-Optical Characterization

The electro-optic response of the fabricated MZI modulator was tested with the setup demonstrated in Figure 11. The setup includes an external tunable laser to generate the optical signal and a polarization controller to launch a TE fundamental mode in the chip. The TE mode couples to the chip via a surface grating coupler and travels through the MZI. It couples out from an output surface grating coupler. The outcoupled light is then fed to the VNA after passing from an Erbium-doped fiber amplifier (EDFA). The RF signal is applied to the signal electrode of the MZI modulator. At the other end, it is terminated with a 50 Ohm load to suppress back-reflections of the RF signal.

Fig. 11. High-frequency electro-optical characterization setup.

The measured S_{21} response, which corresponds to the EO response of the MZI modulator, is recorded and plotted in Figure 12. The 3-dB optical bandwidth is around 10.5 GHz. In the next section, we will analyze these results.

VI. DISCUSSION

A. Equivalent Electrical Circuit Model

To explain the observed behavior of the modulator an equivalent electric circuit model (EECM) is developed. The schematic of the model is presented in Figure 13(a). Each part of the MZI is modeled with a corresponding electrical component. The high n-doped slab act as a resistor and is modeled as R_{hd} . The slot and electrodes with EO polymer in between act as capacitors and are modeled as C_s and C_p in the EECM, respectively. Moreover, a frequency-dependent parasitic resistor, R_{con} , a frequency-dependent parasitic capacitor C_0 and an inductor L_{con} are considered in the EECM to model the electrical behavior of the metal electrodes [20, 21]. R_{con} and C_0 are frequency dependent to capture the frequency dependency of the metal electrode resistance and capacitance. It should be noted that, in our MZI modulator there is no gate voltage [21] applied between the substrate and the InP membrane. Additionally, the Silicon substrate's effect is not considered since the total bonding layer thickness is around 7 μm , and the silicon substrate is a very high resistivity substrate ($> 20000 \text{ Ohm}$).

Fig. 12. Measured EO-response of the fabricated MZI modulator.

Fig. 13. (a) MZI cross section with the corresponding electrical elements representing each part. (b) Equivalent electrical circuit model of the TL of the MZI modulator.

Parameters of the model are obtained from fitting to the measured electrical response of the MZI modulator. The obtained parameters of the electrical model are reported in Table II.

TABLE II
PARAMETERS OBTAINED FOR THE EECM MODEL.

$\frac{R_{con}(\Omega)}{mm\sqrt{GHz}}$	$L_{con}(\frac{nH}{mm})$	$C_s(\frac{pF}{mm})$	$C_p(\frac{pF}{mm})$	$R_{hd}(\Omega \cdot mm)$	$\frac{C_0(pF)}{mm\sqrt{GHz}}$
4.921	0.718	0.139	0.104	55.6	0.136

In Table II, all the values are close to the predicted values except R_{hd} , which is much higher than the expected one ($3 \Omega \cdot mm$). The reason for this discrepancy can be a lower doping concentration than the one assumed ($1 \times 10^{18} \text{ cm}^{-3}$), a thinner slab thickness than the intended one (30 nm), confinement effect of the charge carrier due to the thin thickness, and higher contact resistance than the expected (10^{-6} - $10^{-7} (\Omega \cdot \text{cm}^2)$). It needs further investigations to be determined accurately.

In Figure 14, the actual electrical measurement graphs and the predicted graphs of the model are depicted. It is clear that the model is predicting the behavior of the electrical behavior of the MZI modulator quite accurately.

Fig. 14. (a) S-parameters of the electrical measurement versus the model. (b) The Z_c of the model versus the electrical measurement.

Given the equivalent electrical circuit model, the electro-optical response can be theoretically estimated for the modulator, following Equation 3 [20, 21].

$$R(\omega) = \left| \frac{1 - \rho_1 \rho_2}{1 + \rho_2} \cdot \frac{V_+ + \rho_2 V_-}{e^{i\beta_e L} - \rho_1 \rho_2 e^{-i\beta_e L}} \cdot \frac{1}{(1 + i2\omega R_{hd} C_s)} \right| \quad (3)$$

Where ρ_1 and ρ_2 are the RF source and load reflections, defined as:

$$\rho_1 = \frac{Z_C - Z_S}{Z_C + Z_S}, \rho_2 = \frac{Z_L - Z_C}{Z_L + Z_C} \quad (4)$$

The velocity mismatch between the optical and RF signal is taken into account by:

$$\beta_o = \omega/c n_o, \beta_e = \omega/c n_\mu - i\alpha \quad (5)$$

$V_\pm$ stands for the terms

$$V_\pm = e^{\pm i\varphi_\pm} \cdot \frac{\sin \varphi_\pm}{\varphi_\pm} \quad (6)$$

$$\varphi_\pm = \frac{(\beta_e \mp \beta_o)L}{2} \quad (7)$$

Where n_o and n_μ are optical and RF refractive indices, c is the speed of light in vacuum, L is the length of the phase shifter, and ω is the angular frequency of the input electrical signal. The sign in the subscripts refers to co-propagating (+) and counter-propagating (-) waves, respectively.

As can be seen from Equation 3, the derived normalized electro-optic modulation response includes the influence of the microwave attenuation of the signal, impedance mismatch at both ends of the electrode, and the velocity mismatch between the optical and electrical signal.

Additionally, a correction factor ($1/(1 + i2\omega R_{hd} C_s)$) has been used to account for the influence of the R_{hd} resistance on the effective voltage delivered to the slot (C_s).

If the obtained values are substituted in Equation 3, the normalized electro-optic modulation response can be obtained, as is illustrated in Figure 15. This graph shows that the model is in reasonable agreement with the measured electro-optic modulation response of the MZI modulator.

Fig. 15. Normalized electro-optic modulation response of the measurement (blue curve) versus the model prediction (red curve).

B. Improvement Methods

Using the model developed above, it is possible to study methods to improve the performance of the device.

In Equation 3, many factors influence the modulation response, which could be optimized one by one.

The length of the MZI (L) is one of the factors which plays a crucial role to determine the electro-optical bandwidth. According to Equation 1, if it is assumed that V is fixed and limited to 1 volt and the material properties of the EO polymer and the slot geometry are fixed, the r_{33} value defines L .

In Figure 16, the influence of different lengths, which is hypothetically translated to different r_{33} values (according to aforementioned assumptions; fixed V , w_{slot} , r_{33} , n_{EO} and Γ_{slot}) has been studied. In the case of $L = 187.5 \mu\text{m}$, the 3-dB optical bandwidth is reaching 12.6 GHz. This value decreases when the device gets longer.

Here, the EO bandwidth could not be drastically affected with length variations because other parameters, which will be explained later, dominate the device's performance

Fig. 16. Behavior of the MZI respect to the variation of L (corresponding to r_{33} variation). Longer devices have lower 3-dB optical bandwidth. However, this parameter change is less pronounced in the resulting bandwidth because of the dominance of the other parameters.

The RF source and load reflections can be suppressed if the Z_c of the TL would be closer to the reference impedance (Z_0)

which is 50 Ohm. In Figure 17, the impedance behavior of the TL respect to the design parameters (electrode height, electrode width, and distance of the electrode to the center of the slot) is depicted.

Fig. 17. (a) Z_C versus different electrode height (0.4- 2.5 μm) of the TL. Thicker electrode thickness decreases the Z_C . (b) Z_C versus different electrode width (5- 55 μm) of the TL. Smaller electrode width increases the Z_C (c) Z_C versus different electrode distance (0.9-10.1 μm) of the TL. The optimum electrode distance is around 1.5 μm .

In Figure 17(a), the behavior of the Z_C respect to the electrode height is illustrated. This graph shows the thinner electrode makes the Z_C larger and closer to the Z_0 . However, it should be noted that decreasing the electrode height would increase the RF loss. So, as a trade-off, 600 nm has been chosen for the electrode height.

Figure 17(b) demonstrate that smaller electrode width results in larger Z_C . Likewise, here smaller electrode width increases the RF loss. Considering this trade-off, the electrode width of 20 μm has been selected.

In order to get closer to the Z_0 Figure 17(c) suggests that the electrode distance should be extended. However, on the other hand, increasing the distance would increase the electrical resistance of the highly n-doped slab, which is detrimental to the device performance and adversely affects the electro-optic bandwidth and RF loss. This trade-off imposes the optimum electrode distance to be equal to 1.5 μm .

The other two primary factors which influence the optical bandwidth of the MZI modulator are R_{hd} and C_s , which can be lowered to get higher optical bandwidth. R_{hd} can be lowered by correcting the doping concentration of the high n-doped slab region and reducing the electrode distance. However, if the electrode distance decreases below 1.5 μm , the optical loss would become too high. On the other hand, C_s , also can be reduced by increasing the slot width. This would lead to a lower confinement factor, which is not desirable. In Figure 18, the

relation of these two parameters with the electro-optical response of the MZI modulator is illustrated.

Fig. 18. (a) Influence of different doping level for high n-doped InP slab on 3-dB optical bandwidth, at a slot width of 100 nm. (b) Influence of slot width on 3-dB optical bandwidth, at a fixed doping concentration of $1 \times 10^{17} \text{ cm}^{-3}$.

Taking into account all the factors influencing the optical bandwidth, the best possible design has been identified with the parameters listed in Table III.

TABLE III
PARAMETERS OBTAINED FOR THE IMPROVED DESIGN OF TL.

Electrode width	Electrode height	Electrode distance	Slot width	Rail width	Doping concentration of the slab
20 μm	600 nm	1.5 μm	200 nm	300 nm	$2 \times 10^{18} \text{ cm}^{-3}$

In Figure 19(a), the Z_C , RF loss, RF refractive index, and normalized EO-response of the new TL design are shown. Z_C is around 30 Ohm for the whole frequency range. It is not possible to take this impedance closer to 50 Ohm because of the material properties and fabrication considerations in our design. However, if we bond the InP membrane on CMOS driver circuitry, the 50 Ohm can be avoided since the co-design of electronics and photonics allows a free choice of a reference impedance [22].

As shown in Figure 19 (b), the RF loss is reduced with respect to the previous design.

In Figure 19(c), The effective RF refractive index is shown, which is reasonably close to the effective group index of the optical mode ($n_{TE} \sim 3.6$). This would lead to a low electro-optical walk-off along the TL in operation at high frequencies.

This improved design would enable us to reach beyond 105 GHz 3-dB electro-optical bandwidth, which is higher than the state-of-the-art values (60 GHz) [23] in SOH.

Furthermore, the confinement factor for a 200 nm slot waveguide with 300 nm rail width is 27.7 %, and propagation loss is 0.21 dB/m. Although the confinement factor is slightly lower than the previous design, 3-dB optical bandwidth improvement is very significant.

Fig. 19. (a) The characteristic of the TL versus frequency of the RF signal. (b) RF loss versus frequency of the RF signal. (c) RF refractive index versus frequency. (d) Normalized electro-optic modulation response of the optimized design.

For this new design, thanks to the InP properties mentioned in Figure 1, we opt to use a doping concentration as high as $2 \times 10^{18} \text{ cm}^{-3}$. For this doping level, the additional optical losses compare to the intrinsic InP layer are calculated to be around 1 dB/cm [17]. In fact, this subtle increase is due to the fact that the intentionally highly n-doped epitaxial grown layer has 40 nm thickness and overlap of the optical mode with this highly doped region is limited to that section.

To illustrate the high data transfer rate of the designed modulator, electrical eye diagrams of the fabricated modulator and the optimized version are simulated and compared [24]. The NRZ eye diagrams of the OOK signals for different data rates are shown in Figure 20. As it is clear from Figure 20, the optimized modulator could reach very high data rates with a clear eye-opening.

Fig. 20. The simulated electrical eye diagrams of the fabricated modulator and the optimized version for different data transfer rates with corresponding estimation of Q-factors and bit error rates (BER) (Here an ideal source is considered without any noise). (a), (b) and (c) are electrical eye diagrams obtained from the measurement of the fabricated chip simulated with the available post-measurement analysis software [24]. (d), (e) and (f) are the simulated electrical eye diagrams of the optimized design. Optimized design can reach much higher data transfer rates with clearer eye-openings. (Error-free state has been considered when BER is better than 10^{-9})

VII. CONCLUSIONS

For the first time, an electro-optic slot waveguide phase modulator in the InP membrane on the Silicon platform has

been demonstrated. Low-frequency measurements showed that we could achieve $V_{\pi}L_{\pi}$ equal to 4.5 V.mm with an extinction ratio of 10.6 dB. The 3-dB electro-optical bandwidth of this modulator is measured to be 10.5 GHz. An equivalent electrical circuit model is created in order to analyze the results. Based on this model, a new design is suggested, improving the 3-dB bandwidth to higher than 110 GHz. The eye diagram simulation of the new design showed the capability of this design to transfer data with rates higher than 100 Gbps.

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