A Lateral MOS-Capacitor-Enabled ITO Mach–Zehnder Modulator for Beam Steering

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Abstract—Here, we experimentally demonstrate an Indium Tin Oxide (ITO) Mach–Zehnder interferometer heterogeneously integrated in silicon photonics. The phase shifter section is realized in a novel lateral MOS configuration, which, due to favorable electrostatic overlap, leads to efficient modulation ($V_{\pi} = 63\,\text{V} \cdot \mu\text{m}$). This is achieved by (i) selecting a strong index changing material (ITO) and (ii) improving the field-overlap as verified by the electrostatic field lines. Furthermore, we show that this platform serves as a building block in an end-fire silicon photonics optical phased array (OPA) with a half-wavelength pitch within the waveguides with anticipated performance, including narrow main beam lobe ($<3^\circ$) and $>10\,\text{dB}$ suppression of the side lobes, while electrostatically steering the emission profile up to $\pm 80^\circ$, and if further engineered, can lead not only towards nanosecond-fast beam steering capabilities in LiDAR systems but also in holographic display, free-space optical communications, and optical switches.

Index Terms—Beam steering, electro-optic modulator, indium tin oxide (ITO), LiDAR, Mach–Zehnder, phased arrays.

I. INTRODUCTION

Indium tin oxide (ITO) is a ternary compound which belongs to the class of transparent conductive oxide (TCO). For its coexisting optical and electrical properties, ITO has been extensively used as conductive layer in smartphones [1] and in photovoltaic cells [2]–[4]. When electrically tuned (i.e., capacitively gated), ITO films are able to deliver unity-strong index modulation [5]–[9], especially close to its epsilon-near-zero (ENZ) behavior [10], which leads, inter alia, to significant optical nonlinearities [11], supporting both strong index modulation [12], and slow-light effects [13].

The large interest surrounding ITO, which was mainly pushed due to its use in the industry, product-related purposes and timely applications, enabled high-yield and reliable wafer scale fabrication processes [14], [15], potentially compatible with the CMOS technology production line, which makes this material even more appealing for a plethora of other applications.

In this view, here we experimentally demonstrate a straightforwardly implementable ITO-based Mach–Zehnder interferometer (MZI) electro-optic (EO) modulator utilizing a plasmonic mode. Thanks to favorable electrostatics in the active device region, the overlap of the in-plane component of the electrostatic field is maximized within the ITO layer, yielding an efficient carrier accumulation, thus a pronounced local refractive index variation. This mechanism of this initial prototype device enables an extinction ratio (ER) of $2.2\,\text{dB}$ in a rather compact device (phase shifter length, $L < 2\,\mu\text{m}$) and competitive figure of merit, $V_{\pi} L = 63\,\text{V} \cdot \mu\text{m}$, which suggests that these demonstrated device concepts trade-off rather well between the size ($L$) and the voltage needed to obtain a $\tau$-phase shift ($V_\tau$).

As a straightforward application, this active module could be particularly practical for targeting light detection and ranging (LiDAR) related device. LiDAR is a remote sensing method that uses laser pulses for high precision, long-range motion sensitive detection, which can resolve fine features, largely employed in self-driving cars [16], [17], and geographical [18], archiological [19], and geo-spatial surveys [20]. Although, to be able to scan a sufficiently large field of view a collection of antennas (i.e., free-space emitting waveguides), namely optical phased array (OPA), is used. Similar to their radio-frequency counterpart, by controlling the phase of the emission of each antenna a consistent signal is steered in a specific direction. This allows replacing the otherwise costly and fragile micro-electromechanical devices with integrated photonic systems [21], [22], working in the telecom regime ($\lambda = 1550\,\text{nm}$), with reduced human eye exposure even at sustained power. Currently, the dense integration in silicon photonics enables the fabrication of a...
variety of OPAs for both mono-dimensional and bi-dimensional steering capabilities [23]. 1-dimensional beam steering can be achieved easily through end-fire sub-wavelength pitch array of waveguides; while 2-dimensional steering requires structure-aided emission in the direction orthogonal to the propagating wave, such as grating couplers [24], optical antennas [25], or heterogeneously integrated photonic crystals [26], [27]. However, the main critical aspect to these systems is that they rely on thermo-optical mechanisms for phase shifters which sets limitation in terms of steering rate; beside the implication to the power budget of the system, these devices are still operating at a speed in the kHz range [28], which cannot meet the requirements for robotic-based LiDAR systems, aerospace applications and high-speed communication, while still potentially affected by thermal crosstalk.

Thanks to the fundamentally low RC delay, the modulation speed of ITO based film can achieve bandwidth up to GHz [5], [6]. Here, we use the experimental data of the ITO electro optic modulator to engineer a one-dimensional edge-emitting array of silicon waveguides and studying its performance. Using a $\lambda/2$ spacing (775-nm pitch) at the output, most of the power is conveyed through the main lobe, suppressing grating lobes [24], [29]. We show that the emission is characterized by a narrow profile in its main beam lobe (FWHM $< 10^\circ$) and more than 10 dB suppression of the side lobes, while steering up to $\pm 80^\circ$. We firmly believe that if this prototype phase shifter is further engineered it could be a promising approach towards a high-rate and energy-efficient beam steering platform for future LiDAR systems.

### II. RECENT ADVANCEMENTS IN MACH ZEHNDER MODULATORS

Since phase modulators invariably require interferometric schemes (e.g., ring resonators and MZIs), they do inherently suffer from an extended footprint compared to absorption modulators as those can be realized utilizing just straight waveguides. In MZMs, the product of the half-wave voltage times the active modulator length, $V_nL$, is a figure of merit (FOM) since they exhibit a tradeoff between obtaining $\pi$-phase shift with competing effects in increasing device lengths or bias voltages.

While MZMs based on lithium niobate (LiNbO$_3$) are commercially available, their $V_nL$ is rather high due to the weak Pockels effect, whereas improved performance is obtained with the quantum confined Stark effect (QCSE) in III-V semiconductors or emerging materials such as polymers and enhanced light-confinement for improving optical and RF mode overlap ($\Gamma$) with the active material (Table I). The devices exhibiting advanced FOMs amount to plasmonics, integration of organic/polymer materials, III-V quantum well structures, etc. Many of these schemes essentially offer acceptable performance but are mostly difficult to integrate in the mature Si process. Our design can avail ease of fabrication and potential CMOS integration due to the recent allowance of ITO in (certain) semiconductor foundry processes.

Among the LiNbO$_3$ modulators, three broad categories of schemes can be found: thin plate, ridge waveguides and domain inversion. Ridge waveguides provide step index contrast in the lateral direction. Thin plate LiNbO$_3$ modulators are formed by uniformly thinning down to dimensions of the EO crystal by precise lapping and polishing on a low dielectric substrate (e.g., SiO$_2$) to decrease the effective microwave index such that the modulating electric field is subjected to a higher confinement and forced to be parallel to the crystal z-axis exploiting the maximum EO tensor component ($r_{zz}$). Domain inversion employs opposite phase change in the two arms by unifying the waveguides under the same electrode diminishing chirp effects. While all these schemes do offer several necessary benefits, in terms of the key FOM they are quite limited (Table I). Different approaches using Si as the conventional material of choice have also emerged over the years such as simple metal-oxide-semiconductor (MOS) capacitive gating, employing pn/pin-configurations, selective doping optimizations etc. Different ambitious architectures (e.g., pipin [35], p$^+\cdot$n$^-$ [52]) and techniques (e.g., doping optimization [39], projection structures [45], etc.) on Si based schemes have also been investigated in order to achieve higher modulation performances. The Si p$^+\cdot$n$^-$ forward biased junction device was in the lead of minimizing the attainable FOM until 2011 [43], III-V materials and quantum wells have also been sought after to bring down the FOM in realizing higher performing devices [46], [48], [50]. Hybrid structures using different material and structure combinations have also been investigated [49]. Recent use of organic polymers and hybridization with plasmonic

### Table I: Figure of Merit (FOM) Comparison for Mach—Zehnder Devices with Different Active Modulation Materials and Waveguide Structures in Recent Years

| Structure/Material                  | $V_nL$ (V $\mu$m) | Ref. |
|-------------------------------------|-------------------|-----|
| Si Wrapped around-pa                | 140,000           | [30]|
| Coplanar waveguide LiNbO$_3$       | 120,000           | [31]|
| Si Wrapped around-pa                | 110,000           | [30]|
| Domain inverted push-pull LiNbO$_3$| 90,000            | [32]|
| Dual driven coplanar waveguide LiNbO$_3$ | 80,000          | [31]|
| Si Vertical-pn                      | 40,000            | [33]|
| Bulk LiNbO$_3$ physical limit       | 36,000            | [34]|
| Si pipin                            | 35,000            | [35]|
| Si Lateral-pn                       | 28,000            | [36]|
| Si Lateral-pn                       | 27,000            | [37]|
| Si pn-depletion                     | 24,000            | [38]|
| Doping optimized Si                 | 20,500            | [39]|
| Si Self-aligned-pn                  | 18,600            | [40]|
| Integrated thin film LiNbO$_3$ on insulator | 18,000         | [41]|
| Si pin                              | 13,000            | [42]|
| Silicon-organic hybrid (SOH)        | 9,000             | [43]|
| Si Lateral-pn                       | 8,500             | [44]|
| Si Projection MOS                   | 5,000             | [45]|
| III-V Multiple Quantum Wells (MQW) | 4,600             | [46]|
| SOH                                 | 3,800             | [47]|
| GaAs/AlGaAs                         | 2,100             | [48]|
| Hybrid Si MQW                       | 2,000             | [49]|
| InGaAs/InAlAs MQW                   | 600               | [50]|
| ITO MOS                             | 320               | [51]|
| Si p$^+\cdot$n$^-$                   | 360               | [52]|
| E0 Polymer Plasmonic                | 70                | [53]|
| ITO Lateral MOS                     | 63                | This work |
| Liquid crystals with SOH slot all-plasmonic polymer | 60         | [54], [55]|


structures enabled record-low FOMs [54], [55]. Previously we demonstrated an ITO-based photonic MZI and achieved a modest V_{s,L} despite it being the first of its kind [51]. This paper focuses on a lateral ITO-based MOS-stack enabled MZM device and the achieved FOM in our results seems relatively aligned with the state of the art MZMs and potentially paves the path for dense on-chip packaging for various applications including not only beam steering capabilities in LiDAR systems but also in holographic display, free-space optical communications, and optical switches.

III. ITO MATERIAL PROPERTIES

The ITO material properties were derived by a combination of electrical and ellipsometric spectroscopic (J. A. Woollam M-2000 DI) measurements of the film, as deposited. Dispersion relations for the real and imaginary parts of the complex refractive index, $n$ and $\kappa$, respectively, with regards to states of operation of the device are shown in Fig. 1. The dispersion relations are analytically modeled with fitting parameters obtained from experimental results. Hereafter, the nomenclature regarding the ON-OFF states of operation for the modulator relate to the light transmission (ON) vs. low-transmission (OFF) characteristics through the device, rather than the applied voltage bias. We calculate the carrier concentration for an unbiased film by fitting spectroscopic ellipsometry with Drude Model, extrapolating initial carrier concentration and scattering rate. The variation of the refractive index for a bias is instead derived by the modulation dynamic obtained in the experiment as function of the applied voltage and again fitted with Drude dispersion for an increased carrier concentration. ITO resistivity and sheet resistance was obtained by resistor-transmission line measurements and confirmed by ellipsometry, therefore measured to be $6.2 \times 10^{-4}$ $\Omega$ cm and 37.6 cm$^2$/V-s, respectively. Hall bar tests revealed that the carrier concentration of the as deposited ITO film is $N_c = 2.3 \times 10^{20}$ cm$^{-3}$. The change in the carrier concentration level arising from active capacitive lateral gating is calculated as $\Delta N_c = 1 \times 10^{20}$ cm$^{-3}$. Unlike other work on ITO absorption modulators [5], [6], this low carrier change was selected to reduce optical losses facilitating phase contributions in the obtainable modulation dynamic range.

IV. DEVICE DESIGN, FABRICATION AND RESULTS

We opted for a symmetrical passive MZI structure on a Silicon on insulator (SOI) platform so that the interference pattern at the output can distinguishably confer modulation effects from our active device. A symmetrical MZI structure here means that we choose the same length for both Mach—Zehnder arms and employ equal 50:50 Y-splitters on both sides. This design choice is made as different ratio in the Y-splitters can introduce chirp effects in modulation. Fabrication imperfections such as sidewall roughness, surface defects and alignment issues inherently deter one from achieving perfectly symmetrical MZI structures. Nevertheless, we make this design choice to minimize such effects and curtail the optical path length difference in both the arms of the MZI, to distinguish phase variability only conferring active modulation effects, while further engineering can be performed in an industry setting. The adverse effects of using highly-index modulation materials like ITO is accompanied by increased absorption as a byproduct of modulation relative to field-based modulation such as Pockels effect for example. This absorption in free-carrier materials (e.g., Si, ITO) arises from the well-known Kramers-Kronig (K-K) relations and poses a tradeoff for utilizing such highly tunable active modulation materials [56], [57]. As such, the active ITO in one arm of the MZI imposes a modulating absorption (loss) component, whereas the other (un-modulated) arm throughput a higher optical power as a result. This, in turn, produces an arm loss imbalance in the device, thus limiting the achievable modulation dynamic range as differential loss between the arms due to carrier depletion can limit the ER [58].

For an ideal MZI the basic components i.e., the Y-splitters, arm lengths, arm losses and the phase shifters are perfect, and no issues with residual extinction ratio and chirp are found. In praxis, the Y-splitters do not have perfectly equal power division and the phase shifts in both arms simultaneously do not conjugate each other. Let us model an MZI structure where we choose the same length for both Mach—Zehnder arms and employ equal 50:50 Y-splitters on both sides. This design choice is made as different ratio in the Y-splitters can introduce phase shifts (regardless of whether due to active modulation or fabrication imperfections leading to mismatched arm lengths) are $\Delta \phi_1$ and $\Delta \phi_2$, respectively. If we now assume that the two arms of the interferometer lead to different propagation field losses $a_1$ and $a_2$ respectively, the output field, in general, can be expressed as

$$E = E_0 \left( a_1 p_1 p_2 e^{j \Delta \phi_1 (t)} + a_2 \sqrt{1 - p_1^2} \sqrt{1 - p_2^2} e^{j \Delta \phi_2 (t)} \right)$$

(1)
The input and output fields are denoted by phasor quantities, i.e., \( \widetilde{E} = E e^{j\omega t} \), and assuming there is no gain in the system, \((a_1 + a_2)^2 \leq 1\). It is difficult to comprehend the effect of all the parameters on the extinction ratio and chirp from this expression. Let us, therefore, simplify this expression with the assumption that only the input Y-splitter is imperfect, every other component is ideal and the arm lengths and field losses are balanced, which translates to \( p_2^2 = 1/2 \), \( a_1 = a_2 = a \) and \( |\Delta \phi_1 - \Delta \phi_2| = \Delta \phi \). With these approximations in place, we can obtain

\[
\widetilde{E} = \frac{\widetilde{E}_0}{\sqrt{2}} a e^{j \Delta \phi(t)} \left( p_1 + \sqrt{1 - p_1^2} e^{j/2 \Delta \phi(t)} \right)
\]  

(2)

Now, the extinction ratio (ER) is the ratio of the transmission between the ON state (maximum transmission) and OFF state (minimum transmission), i.e., static ER since it is measured by varying a DC phase bias to one of the arms to find the absolute maximum and minimum transmission. This is necessary since the dynamic ER may be reduced when operating at high frequencies due to limited phase swings or pulse shaping from the finite bandwidth of the electrodes. This upper bound can be referred to as the maximum extinction ratio, \( \text{ER}_{\text{max}} \). For binary modulation schemes \( \Delta \phi = \pm \pi/2 \), and consequentially the extinction ratio becomes

\[
\text{ER} = \frac{p_1 + \sqrt{1 - p_1^2}}{p_1 - \sqrt{1 - p_1^2}}
\]  

(3)

It is noteworthy that for an ideal MZI case, where \( p_1^2 = 1/2 \), the ER is infinite given that both arm losses are perfectly balanced notwithstanding the K-K resultant imbalance or fabrication imperfection leading to the different branches experiencing different optical path travelling in distinct waveguides. To investigate the effects of active modulation at the output, let the Y-junctions be ideal, i.e., \( p_2^2 = p_3^2 = 1/2 \) and all the field losses in the two arms are equal \((a_1 = a_2)\). The output then becomes

\[
\widetilde{E} = a \widetilde{E}_0 e^{j \Delta \phi(t)} = a \frac{\widetilde{E}_0}{2} e^{j \Delta \phi(t)} \cos^2 \left( \frac{\Delta \phi}{2} \right)
\]  

(4)

To maximize the obtainable ER, i.e., ensuring minimal zeros in the OFF state, the field losses in both arms need to be matched, i.e., \( a_1 = a_2 \). Deviations from this ideal case are typically attributed to imperfect 50:50 Y-couplers \([59],[60]\). However, it is critical to emphasize that deviation from \( a_1 = a_2 \) can be a direct result from differences in the losses anywhere in the MZM configuration including possible fabrication imperfections. By contrast, higher index changeable materials (e.g., ITO) do accompany loss as a byproduct of modulation and as such both the states of operation need to be accounted for in design considerations. One can improve this arm loss imbalance by tuning the un-modulated arm losses statically to counteract the imbalances arising from the K-K relations. As such, we chose to deposit metal (Au) on the other (un-modulated) arm of the MZ (Fig. 2(a)). Since the modulation efficiency (ER/peak-to-peak voltage, \( V_{pp} \)) is improved for electrostatics, we use a relatively high-k
dielectric, a 10 nm oxide layer of Al2O3 grown on the passive structure using atomic layer deposition (ALD) to aid capacitive gating schemes. Subsequently, a 10 nm thin film of ITO is deposited using an ion beam deposition (IBD) process after necessary patterning using EBL and lift-off processes afterwards (Fig. 2(b), red dashed area). The IBD process has synergies for processing ITO as this process yields dense crystalline films that are pinhole-free and highly uniform and allows for a room temperature process, which does not anneal ITO (i.e., no activation of Sn carriers as to facilitate electrostatic EO tuning). Incidentally, IBD technologies are advantageous for nanophotonic device fabrication due to their precise controllability of material properties such as microstructure, non-stoichiometry, morphology, and crystallinity [61], [62].

A selective etch step of the ALD grown oxide near the active ITO device region is enacted to facilitate the electric field overlap from the contacts with the active ITO material (Fig. 2(b), white dashed area). Contacts and the plasmonic top layer are formed by depositing 50 nm of Au using electron beam evaporation process. An adhesion layer of 3 nm of Ti is used in the process. The other contact is placed in close proximity (<2 μm) to the plasmonic top contact in the partial etched region to maximize the electrostatic field overlap to the active ITO region (Fig. 2(c)). The schematic of a longitudinal cross-section along the Si waveguide (active arm of the MZI structure) in the device region is illustrated in Fig. 2(c, i) and a cross-sectional schematic of the active plasmonic ITO region is shown in Fig. 2(c, ii). Another contact on the partial etched region is placed for determining the partial etch success; as we aimed for a remainder of just 1-2 nm thin oxide film after etch (Fig. 2(b)), this contact provided the control to determine if etched all the way through to the conductive Si layer.

The pattern transfers were performed in EBL using the Raith VOYAGER tool with PMMA based photoresists, and MIBK:IPA (1:3) developer for 60 s. 50 nm of Au for contacts and the plasmonic top layer in the mode structure were deposited using an e-beam evaporation system (CHA Criterion) as Au has reasonably low ohmic loss at near IR wavelengths. An additional 3 nm adhesion layer of Ti was used in the contacts. The Al2O3 oxide was deposited using the ALD technique as it provides reliable and repeatable performance characteristics. The Fiji G2 ALD tool was used at low temperature settings (100°C) for 100 cycles to deposit about 10 nm of Al2O3 to ensure higher film quality devoid of any pinholes or surface traps. A Filmetrics F20-UV system was used to characterize the Al2O3 deposition rate.

An etch step was required for the partial etch near the active device region to facilitate the necessary height contrast between the plasmonic top contact and the lateral bottom contact in the MOS-stack. We used a rather slow wet etch process for Al2O3 using an MF319 solution in the area of interest (near the active ITO region, keeping the both contacts sufficiently close in proximity without jeopardizing etching on the extended active ITO region). Note, MF319 contains tetramethylammonium hydroxide (TMAH), which reacts with the Al and can etch the oxide thereof.

Experimental I–V measurements of the device show a working capacitor in the measured voltage range, not showing any observable saturation of the MOS capacitor or breakdown of the gate oxide characteristics (Fig. 3(a)). Electro-optic transmission power tests via a gated-transmission measurement exhibit reasonable modulation of the laser power demonstrating a modulation depth (i.e., ER) of ~1.34 dB in the measured bias range, and a squared cosine fit (as dictated by the underlying physics of MZIs from Eq. (4)) can obtain an ER of 2.2 dB. The quality of the fit symbolized by the coefficient of determination (R²) is 0.86. The voltage needed for π-phase shifts at the optical output is about 33 V (Fig. 3(b)) and a corresponding VπL of just 63 V/μm given the <2 μm-short phase shifter.

In order to gain more insights into the field-distribution of this lateral-gated modulator, finite element method (FEM) simulations are carried out to resolve the electrostatic field overlap with the active ITO arising from capacitive gating which confirms an increased field overlap due to the partial etching of the oxide (Fig. 4). Here we use the aforementioned carrier concentration of 2 × 10²⁰ cm⁻³ and 1 × 10¹⁴ cm⁻³ for ITO and Si, respectively. The plasmonic optical confinement in the active region further acts to amplify the material index change into obtainable effective modal index variation; hence aiding the overall modulation depth arising from both effects (traditional plasmonics and improved electrostatics in the lateral configuration). As both plasmonic top contact and the bottom contact in the capacitive stack are only metal paths, there is little resistance...
leading up to the device region; so, such a device is only limited by the capacitance (not R-limited) in terms of attainable speed. Selective plasma treatment on the ITO contact region can avail lower contact resistances up to 2 orders of magnitude [9]. The switching speed of such modulators are essentially limited by the dynamics of majority carriers in the ITO film, and optimally, speeds in GHz ranges should be feasible as demonstrated in other majority carrier-based devices [63]–[65]. Footprint efficient modulators can also help in photonic-electronic hybrid integration for network on chips [66], and we envision emerging EO material heterogeneously integrated in foundry-ready photonic circuits to be a key driver in a modulator roadmap [67], [68].

V. OPTICAL PHASED ARRAY

In this section, we proceed to numerically demonstrate a first design of an optical phased array system constituted by such ITO phase modulators using this hereby introduced lateral capacitor configuration (Fig. 5). The scheme consists of an edge-emitting one-dimensional (end-fire) array of silicon waveguides. A coherent radiation is split into several channels (waveguides) using a power splitter tree. Each branch is then fed to a tunable phase shifter. The opportunity phase shifted light reaches the termination of the closely spaced waveguide at the end of the chip thus coupling into free space. The radiation of each element interferes in the far-field forming specific radiation patterns according to the modulated phase difference between neighboring waveguides similar to phased array antenna for enhancing directionality in radio wave transmission. The properties of the radiation pattern can be tuned through a carefully selected spacing and number of emitting apertures, obtaining arbitrary narrow lobes. Usually the variation of the phase of the light is obtained by thermally tuning the refractive index via heating, cooling or utilizing Pockels effect, such as in lithium niobate. In our case, we opted for phase tuners relying on carrier injection. By adjusting the concentration of free carriers, we vary the optical path length, and hence, the phase of the radiation emitted. Devices relying on carrier dynamics are much faster than those relying on thermal tuning and more compact than Pockels or Kerr effect-based devices. The combination of these properties enable the fabrication of potentially fast and µm-size compact beam-steering platform. In this study, ITO-based phase modulators are used to change the effective optical path length of each channel and finely control the emitted phase at its edge.

Ultimately, the waveguides approach each other in a 1-D array of end-fire antennas with sub-wavelength pitch (λ/2), hence emitting the beam from the edge of the chip. An overview of such a beam-steering scheme is illustrated in Fig. 5(a). With the phase tuning efficiency of the lateral-MOS capacitor ITO Mach—Zehnder modulator characterized, it is possible to achieve phase shifts in plane with the waveguides (horizontal direction).

The steering in ψ for a uniform array is determined by sinψ = ϕ/2πd, where ϕ is the uniform phase difference between the adjacent array elements, λ is the free-space wavelength of the laser, and d is the element spacing. Straightforwardly, the maximum steering angle can be achieved when d equals to half the wavelength (d = 775 nm). Under this condition, we were able to prevent the formation of prominent grating lobes in the emission pattern, which would otherwise cause (a) aliasing due to the presence of more than one lobe in the radiation pattern, limiting the detectable steering angle; (b) reduced power in the main lobe (poor directivity); and (c) non-effective communication system which can suffer from eavesdropping. Additionally, the high confinement in the Si waveguide allows for minimal crosstalk between channels when placed at rather small distances. For further mitigating the crosstalk, the waveguides are routed closely to one another gradually towards the far end of the array where they emit in free space. From FDTD simulation and numerical modelling, we first derived the far-field (Fraunhofer diffraction) emission pattern of our waveguide, subsequently we simulated the end-fire optical phased array platform by studying the light emission of multiple waveguides. We then simulated far-field interference among the waveguides using a MATLAB script. The maximum steering angle achievable through electrostatic tuning of ITO based OPAs, for 8 waveguides, can reach ±80° (Fig. 5c). Also, in this case, the maximum side lobe level (SLL) is more than 5 dB throughout the steering angle with an average beam width of 20°. However, this large beam width can be considerably decreased by augmenting the number of waveguides in the end-fire array. The SLL decreases significantly due to increased numbers of waveguides in the array and for 128 waveguides, the suppression is larger than 10 dB (Fig. 5(b)). Moreover, in Fig. 5(c), the beam width (FWHM) decreases from ~20° to less than 3° by increasing the number of arrays from 8 to 128. It is worth mentioning that the model does not account for optical losses induced by: (a) reflectance between waveguide and free space; and (b) optical losses in each waveguide due to the different refractive index modulation. The first type of losses can be easily neglected since for single-mode silicon waveguides used in our platform, these are typically well below 1 dB. On the other hand, those induced by phase modulation could potentially limit the sidelobe suppression, introducing unwanted sidelobes and leading to a non-uniform power delivery as function of the steering angle or aliasing when more complex wavefronts are engineered. Although, considering the limited scale of the device (<2 µm) and related contained losses for large phase modulation amongst neighboring channels (π/2), the optical losses due to electrostatic tuning would play a substantial role only for a meager number of elements, in which the main lobe could be overwhelmed by the emerging sidelobes due to unwanted losses.
The introduction of delay lines in each channel maximizing the overlap with the ITO tunable layer can contemporary minimize the modulation voltage required for steering the beam while keeping a compact lateral footprint.

VI. CONCLUSION

In conclusion, we have hereby demonstrated an MZI ITO-based electro-optic modulator, in a lateral capacitor configuration, which leads to favorable electростatics and enhance the carrier tunability in the ITO film, thus delivering competitive performance in terms of figure of merit of $V_L = 63 \text{ V} \cdot \mu \text{m}$ for a $<2 \mu \text{m}$ compact phase shifter. Using this modulator as a phase shifter as a building block of a 128-waveguides end-fire optical phased array beam steering platform, we find a rather fine narrow shaping of the main beam lobe ($<3^\circ$) and $>10$ dB suppression of the side lobes, while steering up to $\pm 80^\circ$ emission profile. This approach has the potential to reduce loss in current OPA design, and yet availing of the ITO GHz-fast modulation speed, for the next-generation LiDAR systems, holographic displays, free-space optical communications, and optical switches.

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Fig. 5. (a) Schematic representation of an phased array end-fire beam steering platform using ITO lateral capacitor modulators. (b) Beam profile for a phased array which comprise of 32 (red), 64 (blue), and 128 (black) waveguides. (c) Beam steering radiation pattern for increasing phase variation between neighboring elements (red 180° to black 0°).
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