Sub-wavelength GHz-fast broadband ITO Mach–Zehnder modulator on silicon photonics

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Here we demonstrate a spectrally broadband, gigahertz-fast Mach–Zehnder interferometric modulator exhibiting a minimum voltage $V_m L = 95 \text{ V} \cdot \mu\text{m}$, deploying a subwavelength short electrostatically tunable plasmonic phase shifter based on heterogeneously integrated indium tin oxide thin films into silicon photonics. © 2020 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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Indium tin oxide (ITO), belonging to the class of transparent conductive oxides, is a material extensively adopted in high-tech industry such as in touchscreen displays of smartphones or contacts for solar cells. Recently, ITO has been explored for electro-optic modulation using its free-carrier dispersive effect enabling unity-strong index modulation [1–3]. However, gigahertz (GHz)-fast modulation capability using ITO is yet to be demonstrated—a feature we show herein. Given the ubiquitous usage of phase-shifter (PS) technologies, such as in data communication, optical phased arrays, analog and RF photonics, sensing, and so on, here we focus on a Mach–Zehnder interferometer (MZI)-based modulator to demonstrate a comprehensive platform of heterogeneous integration of ITO-based opto-electronics into silicon photonic integrated circuits (PIC). Since the real part of the optical refractive index ($n$) is of interest in PSs, in previous studies we have shown the interplay between a selected optical mode (e.g., photonic bulk versus plasmonic) and the material’s figure of merit $(\Delta n/\Delta \alpha)$, where $\alpha$ is the optical loss, directly resultant from Kramers–Kronig relations [4]. Additionally, ITO can be selectively prepared (via process conditions [5]) for operating in either an $n$-dominant or $\alpha$-dominated region [4], demonstrating a photonic-mode ITO-oxide-Si MZI on silicon photonics with an efficient $V_m L = 0.52 \text{ V} \cdot \mu\text{m}$ [2] and a plasmonic version deploying a lateral gate exhibiting a $V_m L = 0.063 \text{ V} \cdot \mu\text{m}$ [6]. Indeed, a plasmonic mode enables a strong light–matter interaction (e.g., extrinsic slow-light effect), which, when superimposed with ITO’s intrinsic slow-light effect, proximal epsilon-near-zero (ENZ) effects [7], enables realization of just 1–3 $\mu\text{m}$ short PSs [4], allowing small ($\sim\mu\text{F}$) electrical capacitances for efficient and fast signal modulation. Here we design the ITO material parameters to control operation in the $n$-dominant region adequately close to but not at the high-loss ENZ (ENZ located in the $\alpha$-dominant region) [4]. In fact, unlike lithium niobate (LN) optoelectronics requiring careful crystal-orientation control [8,9], ITO thin films are crystal-orientation independent and feature intrinsically uniform optical characteristics as deposited. Here we discuss an ITO-plasmon-based PS heterogeneously integrated into a silicon photonic MZI delivering GHz-fast broadband modulation and thus open opportunities for multispectral operation.

The base interferometer is taped out as a symmetric silicon-on-insulator (SOI) MZI to minimize chirp effects induced by different splitting ratios in the Y junctions of the MZI and includes post-tape out loss balancing between both arms using a metallic strip ($L_d$) on the nonmodulated arm to minimize extinction ratio (ER) degradation [Fig. 1(a)]. Sweep of the active PS device length ($L_d$) ranges from sub-$\lambda$ (1.4 $\mu\text{m}$) to $\lambda$-scale devices (3.5 $\mu\text{m}$) [Fig. 1(b)]. Broadband spectral response is measured in the C band ($\sim30$ nm, Fig. 2(a)], which is expected since the plasmonic resonance of the mode has a FWHM $\sim100$s of nanometers (nm). The spectral response is determined by ITO dispersion and

![Fig. 1](image-url)
proximity to the ENZ. For ultrabroadband applications (e.g., 100+ nm) ITO modulators for different spectral regions (e.g., Δλ = 50 nm) can be processed using different conditions [5]. Functional capacitor traits in the measured bias range are observed [Fig. 2(b)]. DC electro-optic transmission power tests and squared cosine fit (dictated by Mach–Zehnder operating principle) result in an ER of ~3 to > 8dB, respectively [Fig. 2(c)]. The measured $V_\text{on} \cdot L$ is just 95 ± 2 V · μm and rather constant across all device scaling.

The results indicate a modal index change $\Delta n_{\text{eff}}$ of ~0.2 [Fig. 2(d)], and FEM eigenmode analysis [inset, Fig. 1(b)] reveals an ITO index change of about 0.6 [Fig. 2(e)] reflecting an ~2× increased confinement factor (Γ) corresponding to active biasing, slightly lower than previous ITO modulators [2], and intentionally enabling lower insertion loss (IL) of about 6.7 dB. Cutback measurements reveal 1.6 dB/μm propagation loss in the active region and an additional 1.3 dB/coupling loss from in/out coupling of the mode from the Si waveguide, while the passive loss balancing contact [Fig. 1(a)], $L_4$ exhibits a 1.2 dB/μm propagation loss and 1.1 dB/coupling loss, correspondingly. Note that the high loss per unit length in plasmonics is alleviated by an enhanced light–matter interaction enabling $\lambda$-short device lengths ($L_4$); thus the total IL is comparable to Si photonic MZIs. The deposited ITO thin film carrier concentration $N_c$ of $3.1 \times 10^{20}$ cm$^{-3}$ is determined from metrology, and a change $\Delta N_c = 2.1 \times 10^{20}$ cm$^{-3}$ estimated from the gated measurements suggests $n$-dominant operation, however intentionally away from the high-loss ENZ ($6 - 7 \times 10^{20}$ cm$^{-3}$) state, yet sufficiently near to capture a slow-light effect [4].

Frequency response ($S_{21}$) is obtained by generating a low power modulating signal (0 dBm) with a 50 GHz network analyzer; a bias tee combines DC voltage (6 V) with the RF signal [Fig. 2(f)]. RF output from the modulator is amplified using a broadband erbium-doped fiber amplifier (EDFA, ~35 dB), and an optical tunable filter reduces undesired noise by 20 dB. The modulated light is collected by a photodetector. The −3 dB roll-off (small signal) shows a speed of 1.1 GHz [Fig. 2(g)], which matches estimations for the RC delay given capacitance of 213 fF and total resistance of 680 Ω, while dynamic switching energy (~pJ) characterizes the spectral trade-off [2]. Performance comparison of this ITO paradigm with recent modulators shows similar achievable speeds, allowing for CMOS low drive voltages and competent $V_\text{on} \cdot L$ enabled by efficient electrostatics ($\varepsilon_\text{Si} = 5$ nm, $\varepsilon_\text{ITO} \times d_4$, pad-overspray optimization, annealing, plasma treatment), which is fundamentally challenging in LN due to its delicate loss sensitivity (Table 1).

This GHz-fast broadband integrated modulator bears relevance since ITO is a foundry-compatible material. Unlike the crystal-orientation-sensitive LN, ITO optoelectronics is synergistic to enhancing electrostatics known from transistor technology.

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**Disclosures.** The authors declare no conflicts of interest.

### REFERENCES


### Table 1. Comparison with Recent Art

<table>
<thead>
<tr>
<th>Type</th>
<th>$V_\text{on} \cdot L$ (V · μm)</th>
<th>$f_{-3\text{dB}}$ (GHz)</th>
<th>IL (dB)</th>
<th>$L_4$ (μm)</th>
<th>$V_\text{bias}$ (V)</th>
<th>E/bit (fJ)</th>
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<tr>
<td>Thin-film LN [8]</td>
<td>28,000</td>
<td>45</td>
<td>0.4</td>
<td>20,000</td>
<td>2.3</td>
<td>14</td>
</tr>
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<td>LN plasmon [9]</td>
<td>3000</td>
<td>9</td>
<td>5.5</td>
<td>20</td>
<td>50</td>
<td>1,000</td>
</tr>
<tr>
<td>EO plasmon [10]</td>
<td>120</td>
<td>70</td>
<td>6</td>
<td>10</td>
<td>12</td>
<td>110</td>
</tr>
<tr>
<td>BaTiO$_3$ (BT) [11]</td>
<td>4500</td>
<td>35</td>
<td>14.5</td>
<td>300</td>
<td>2.5</td>
<td>96</td>
</tr>
<tr>
<td>EO polymer [12]</td>
<td>–</td>
<td>110</td>
<td>2.5</td>
<td>6</td>
<td>3.3</td>
<td>12</td>
</tr>
<tr>
<td>ITO* (This work)</td>
<td>95</td>
<td>1.1</td>
<td>6.7</td>
<td>1.4</td>
<td>20</td>
<td>2046</td>
</tr>
<tr>
<td>ITO (Future option)</td>
<td>3</td>
<td>40.2</td>
<td>3.8</td>
<td>1.0</td>
<td>2.2</td>
<td>19</td>
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