Ultralow Voltage Folded Electro-Optical Modulators in Thin-Film Lithium Niobate Foundry Process

Alberto Della Torre*, Homa Zarebidaki, Jacopo Leo, Arno Mettraux, Andrea Volpini, Davide Grassani, Ivan Prieto, Olivier Dubochet, Michel Despont, Hamed Sattari
(1) Swiss Center for Electronics and Microtechnology (CSEM), Neuchatel, Switzerland
Corresponding author: alberto.dellatorre@csem.ch

Abstract: Electro-optical modulators at 1550 nm wavelength with a V_π as low as 0.21 V are presented. The folded devices, occupying an effective length of 1.5 cm, are manufactured in a foundry process following design rules.

1. Introduction

Electro-optical modulators based in photonic integrated circuits (PICs) are essential components optical telecommunications. The ability of these modulators to function at CMOS-level voltages is vital for seamless integration with electronic components, facilitating efficient photonics-electronics interfaces, addressing the urgent need for power efficient modules. Among the different PICs platforms, thin-film lithium niobate (TFLN) on insulator technology stands out with unique features like a broad transparency window, low optical loss, and a high electro-optic (EO) coefficient. This makes it an exceptional choice for highly efficient optical modulators [1].

Various PIC platforms are dedicated to achieving efficient and dependable optical modulation, primarily leveraging the material properties of the stack. Silicon, lacking second-order nonlinearity, resorts to modulation schemes based on plasma dispersion [2]. Despite attaining a sub-1 V half-wave voltage [3], there exists a fundamental trade-off involving voltage, bandwidth, and optical losses, imposing inherent limitations. Thermo-optical [4] and micro-electro-mechanical systems (MEMS) [5] modulators, despite extensive research, need to tackle challenges like slower thermal response and higher power consumption. In contrast, TFLN stands out due to its superior electro-optic (EO) properties, offering the potential for low-voltage, low-power, and high-speed modulation [6]. TFLN modulators have demonstrated a voltage-length product of 0.64 V.cm [7] and a bandwidth exceeding 100 GHz [8].

In applications within the DC domain, it is widely recognized that there exists an inverse relationship between the length of an EO modulator and its half-wave voltage. While this design principle tempts designers to decrease the modulator's operating voltage by increasing its length, such a strategy comes at the cost of increased chip area. A clever workaround to accommodate a lengthy EO device within a confined area is to employ folding techniques [9,10]. Here we report folded EO Mach-Zehnder Modulators (MZMs) fabricated using a standard foundry process and operating at ultralow voltages. This was achieved through strategic utilization of waveguide crossings and the incorporation of two levels of metallization layers to ensure efficient operation.

2. Results and discussion

The layout of the folded MZI modulator demonstrating our technology layers is presented in Fig. 1(a). The circuit encompasses a series of optimized building blocks from the process design kit (PDK), such as MMI beam splitters, waveguide crossing, and edge coupler [11]. The optical arms and the electrodes undergo several 180° turns, allowing to increase the signal length while keeping the design compact. We adopted a push-pull configuration for the electrodes, in order the minimize the half-wave voltage.

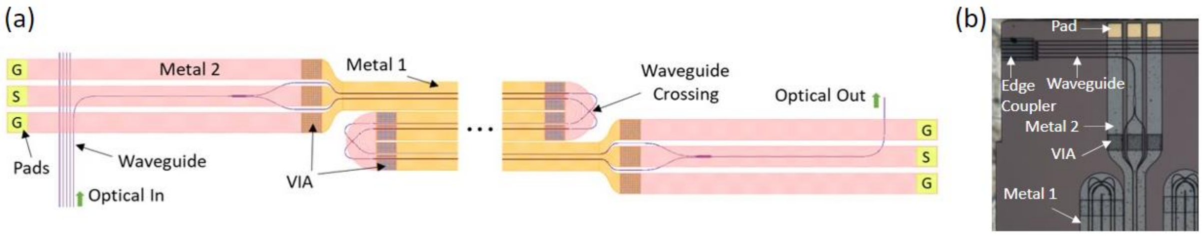

Fig. 1: (a) Schematic view of a folded modulator. Low loss waveguide crossings and two metal layers facilitate accommodating a long device in an effective shorter length. (b) Optical image of the fabricated chip.

The devices are fabricated in a 150 mm wafer-scale standard foundry process at CSEM. Our fabrication technology is based on commercially available thin film LNOI wafers which consist of a stack with 600 nm thick mono-crystal x-cut $LiNbO_3$ layer on top of a 4.7 µm buried thermal oxide (BOX) layer. This PIC platform features a dual-layer metallization structure that enhances the radio frequency routing process and complex electrical circuitry routing, providing a more efficient path for signal transmission. In the platform, all layers are protected by a silicon oxide cladding. Then, a specialized layer, referred to as "clad open", is incorporated to provide designers the option to selectively remove the cladding. This feature allows for specific applications, such as creating access points to the metal pads or directly interfacing with the waveguides. An optical image of the final chip is shown in Fig. 1(b).

For the DC characterization of the modulators, light from a mode hop free laser emitting at 1550 nm is sent to the LNOI chip through a polarization controller, which selects TE polarization, and a lensed fiber. A triangular electrical signal with 1 V peak-to-peak amplitude and a frequency of 1 kHz is applied to the electrodes through ground-signal-ground (GSG) electrical probes. The modulated optical output is recorded by a photodetector with a bandwidth of 11 MHz, whose response is acquired using a 500 MHz bandwidth oscilloscope. Fig. 2(a) shows the modulated optical response of a 11.97 cm long modulator as a function of the applied electrical signal, with a measured half-wave voltage V_π of 0.21 V. This value falls withing the CMOS-level-voltage operation that brings a substantial advantage for the EO modulator enabling to drive the device with fully integrated CMOS electrical circuits, without the need of off-chip amplification. Thanks to our folded modulator design, we achieved such value in a compact 5mm × 15mm chip. Such a chip size could accommodate multiple of folded modulators. Fig. 2(b, left) shows the measured half-wave voltage of 5 different modulators as a function of their length. As expected, V_π decreases with the length, highlighting the importance of the folded design to achieve low V_π in a compact chip. We expect an insertion loss of 3 dB per facet and a propagation loss of 1 dB/cm from the waveguides. However, the metal proximity to the waveguides and local fabrication defects might add an excess loss to the system. For example, for the longest modulator with 10 folds we obtain a total insertion loss of 29 dB including all the components in the light path between the laser to the detector. We also calculate an average modulation efficiency of 2.59 V*cm which is in excellent agreement with what expected when comparing with efficiency of the standard PDK straight modulators. Fig. 2(b, right), shows the modulators electrical-electrical (EE) bandwidth. Further developments are required to increase the bandwidth while keeping the V_π in CMOS operation voltage level, circumventing the conventional voltage-bandwidth tradeoff.

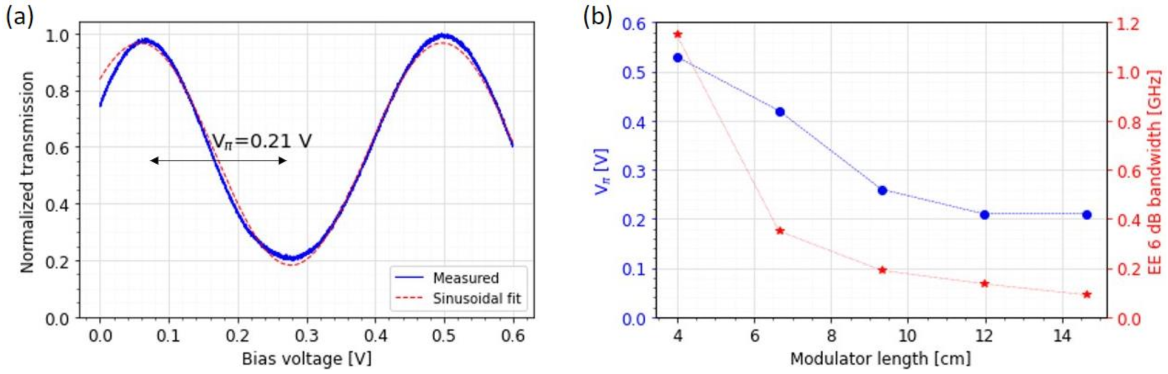

Fig. 2: (a) Measured (blue) and fitted (red) EO response of a 11.97 cm long folded modulator with V_π=0.21 V. (b) V_π measured in different modulators as a function of the modulator length (blue markers) and corresponding EE bandwidth (red markers).

5. Conclusion

We have presented the electro-optical characterization of folded Mach-Zender modulators, manufactured in our TFLN PICs foundry. These modulators demonstrate an ultralow half-wave voltage of below 1 V, all within a compact footprint. This holds great potential for low power integrated electro-optical circuits seamlessly interfacing with CMOS electrical circuits. The success of this device serves as a validation of our standard fabrication process.

Acknowledgments

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