BTO-enhanced silicon photonics – a scalable PIC platform with ultra-efficient electro-optical modulation

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Abstract: We demonstrate an advanced BTO-enhanced silicon photonic platform for high-volume applications in communication, optical computing, and sensing. Our platform exploits an ultra-strong Pockels effect, enabling large-scale, high-speed electro-optic photonic circuits with low power consumption and loss. © 2022 The Author(s)

1. Introduction

Driven by the challenge to handle our exploding global data traffic, silicon photonics has emerged as an important technology to process and convert optical signals. It has evolved as a cost effective, scalable platform for integrated photonic circuits (PICs) by leveraging existing know-how and infrastructure from the electronics industry. PICs based on silicon are applied in a variety of applications, ranging from high-bandwidth data communication, sensing, and beam-steering, to optical quantum information processing units and accelerators.

In all those applications, electro-optic modulators, switches, and tuning elements are performance-critical components. They often represent important bottlenecks in the chip and system performance. Fast and efficient modulators are essential to reach high data rates in communication, low-loss switches are crucial to route signals for network reconfiguration or computing, and low-power tuning elements are important to compensate temperature fluctuations and imperfections during fabrication. Today, those electro-optical components are made in silicon photonics by exploiting the plasma-dispersion effect in PIN-junctions [1], or by using Joule heating [2] because the necessary technologies is readily available in standard silicon photonic fabrication processes. However, there are severe limitations when using those components in high-performing PICs: High insertion losses and residual amplitude modulation are present in highly doped and hence fast plasma-dispersion-effect based modulators; high-power consumption and thermal crosstalk exist in heater-based tuning elements. These limitations can be solved by realizing modulators and switches based on the Pockels effect: The Pockels effect represents a way for electro-optical control at high-speed, low-power, and low-loss and has been utilized in bulk lithium niobate (LN) devices for decades [3]. All materials available in standard silicon photonics however lack the presence of a Pockels effect. New materials with a non-vanishing Pockels effect need to be integrated into silicon photonic to enable Pockels-based electro-optic devices.

In recent years, several material systems have been explored as candidates for introducing the Pockels effect into silicon photonics, such as silicon-organic-hybrids (SOH) [4], PZT-based SiN photonics [5], or thin-film $LiNbO_3$-on-insulator (LNOI) [6]. In standalone devices, very strong performance metrics have been shown, including the demonstration of record-high bandwidth modulators. However, when moving beyond research demonstrations, those technologies suffer various challenges, such as, large device footprints in the centimeter range due to small Pockels effects which limits PIC scalability, integration-incompatibility with large scale silicon photonics production and packaging, low maturity of material fabrication processes, and optical as well as thermal degradation during fabrication and operation.

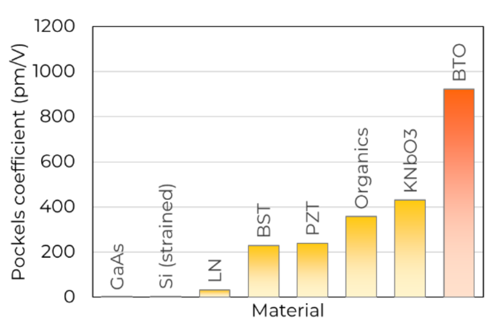

Fig. 1 Comparison of the Pockels effect in different material systems

Those challenges have been solved for barium titanate (BTO) thin films integrated in silicon photonic devices. BTO represents a material system with an ultra-strong Pockels effect of ~1000 pm/V in bulk crystals, which is 30-times larger than in lithium niobate (Fig. 1) and which enables the realization of electro-optic devices with small footprint and high density. The compatibility of the fabrication of BTO with large-diameter silicon wafers and good chemical stability allow the integration of BTO into a scalable, high-volume, commercially available silicon photonic platform compatible fabrication process with excellent performance and reliability metrics [7].

2. Results and discussion

At Lumiphase, we developed a technology to realize BTO-based photonic phase shifters embedded in a silicon PIC environment in which both standard silicon photonic components as well as new Pockels phase shifters are available. Our fabrication process is compatible with high wafer volumes as needed for applications in the fields of communication or sensing.

Efficient phase shifters exploiting a very large Pockels effect of $r > 500$ pm/V [8] can be realized by applying a voltage to electrodes in BTO-based waveguides, embedded in silicon oxide environment (Fig. 2, left). The voltage results in an electric field E in the BTO layer which causes a change of the real part of the refractive index $\Delta n \approx r \times E$. The change of the refractive index can be exploited in high-speed modulators for encoding data signals and lower speed phase shifters for tuning and switching.

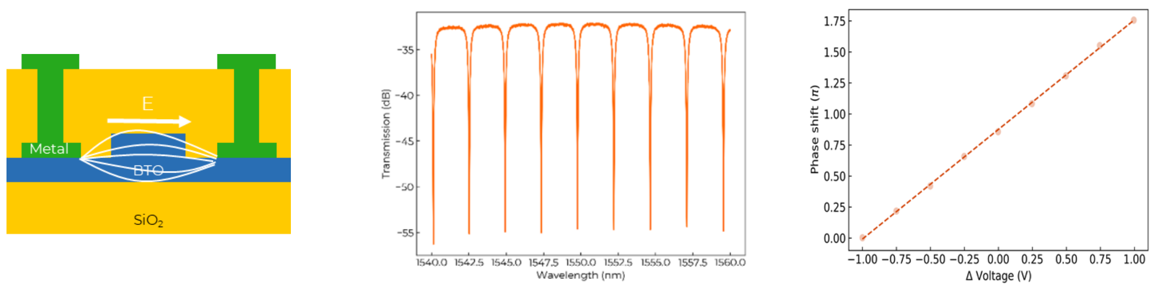

Fig. 2 (left) Example of a cross section of BTO-based photonic phase shifter with two electrodes that can be used to create an electric field (white lines) in the waveguide region. The field causes a change of the refractive index which can be used for modulation and switching. (center) Example of a transmission spectrum of a BTO-based ring resonator. (right) Phase shift in a BTO-based phase shifter as a function of applied voltage.

The low propagation losses of <3 dB/cm in BTO-based waveguides allow the realization of passive components such as splitters, couplers, or high-Q resonators (Fig. 2, center). Since adding electrodes to the waveguides does not impact propagation losses, low insertion losses of sub-dB are well-achievable in active modulators, for example based on Mach-Zehnder-interferometers layouts.

Applying a voltage to BTO-based phase shifters enables a linear change of the optical phase (Fig. 2, right) with small V_π values. Depending on the actual application, phase shifter with ultra-high bandwidth, extremely low insertion losses, and very small voltage operation can be realized by adjusting key design parameters such as device length or electrode layout. Since BTO is an insulator with a voltage driven optical phase shift, ultra-low power consumption of tens of nWs per π-phase shift can be achieved [9] which enables the realization of large-scale circuits with thousands of phase shifters with little cross talk and power consumption as required in switch matrices and large interference networks.

3. Summary

With major breakthroughs in the past years, BTO has emerged as a solution for a new generation of electro-optic devices. Major achievements of the BTO technology have been reached, ranging from important materials aspects, device development, integration concepts, and novel applications in the area of high-speed communication, computing, and sensing. At Lumiphase, we developed such BTO technology as a commercial technology embedded in a silicon-based photonic platform.

Acknowledgement

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References

[1] G. T. Reed, G. Mashanovich, F. Y. Gardes, and D. J. Thomson, "Silicon optical modulators," *Nat. Photonics*, vol. 4, no. 8, pp. 518–526, 2010

[2] A. H. Atabaki, A. A. Eftekhar, S. Yegnanarayanan, and A. Adibi, "Sub-100-nanosecond thermal reconfiguration of silicon photonic devices," *Opt. Express*, vol. 21, no. 13, p. 15706, 2013

[3] E. L. Wooten *et al.*, "A review of lithium niobate modulators for fiber-optic\ncommunications systems," *IEEE J. Sel. Top. Quantum Electron.*, vol. 6, no. 1, pp. 69–82, 2000

[4] C. Kieninger *et al.*, "Ultra-high electro-optic activity demonstrated in a silicon-organic hybrid modulator," *Optica*, vol. 5, no. 6, p. 739, 2018

[5] K. Alexander *et al.*, "Nanophotonic Pockels modulators on a silicon nitride platform," *Nat. Commun.*, vol. 9, no. 1, p. 3444, Dec. 2018

[6] C. Wang *et al.*, "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature*, 2018

[7] "Lumiphase AG." www.lumiphase.com.

[8] S. Abel *et al.*, "Large Pockels effect in micro- and nano- structured barium titanate integrated on silicon," *Nat. Mater.*, vol. 18, no. 1, pp. 42–47, 2019

[9] J. E. Ortmann *et al.*, "Ultra-Low-Power Tuning in Hybrid Barium Titanate-Silicon Nitride Electro-optic Devices on Silicon," *ACS Photonics*, vol. 6, pp. 2677–2684, 2019