Advances in Thin-Film Lithium Niobate Photonics for Datacom Applications

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Abstract: We review recent developments in thin-film lithium niobate photonics to enable high-capacity and energy-efficient optical integration solutions for next-generation datacom. © 2024 The Author(s)

1. Introduction

Lithium niobate, renowned for its superior material properties such as a linear and strong electro-optic (EO) effect (Pockels effect, $\gamma 33 \approx 30$ pm/V) and a broad transparency window (0.4–5 μm), has been a cornerstone for electro-optic modulators in optical data communication networks for decades. Historically, these modulators have relied on titanium-diffused waveguides. However, the advent of thin-film lithium niobate (TFLN) wafers alongside advanced etching technologies has spurred a revolutionary shift in EO modulator design and performance. These etched waveguides enable highly confined optical modes, which facilitate closer metal gap spacings while still maintaining low absorption loss, making modulation much more efficiency thus smaller footprint. Progress in low-loss dry-etching [1-3] and chemo-mechanical polishing [4] of waveguides enhanced by microfabrication techniques such as electron beam lithography (EBL) and photolithography, has elevated TFLN photonics integrated circuits (PICs) to a level where dense integration and mass production are not just feasible but promising.

Regardless of whether it is for traditional pluggable optical modules or the increasingly prevalent co-packaged optical modules within datacom, the need for electronic integrated circuits (EICs), and PICs to enable high-speed EO interfaces and on-chip light manipulation is endless. TFLN has demonstrated immense potential in constructing high-performance optical engines. Such engines are comprised of building blocks that include ultra-high-speed EO modulators compatible with CMOS drivers [5,6], low-loss passive photonic components [7,8], lasers [9,10], and photodetectors [11,12], all of which have been presented recently. In this paper, we will review TFLN-based PIC tailored for optical engines and engage with the ongoing challenges faced by TFLN photonics in the realm of data communications. Specifically, we will evaluate and deliberate on the superior performance of TFLN modulators in data transmission, reviewing their performance in both short-reach and long-haul applications

2. TFLN transceiver

The conceptual architecture of the proposed TFLN coherent optical engine is depicted in Figure 1. The design seamlessly integrates both a transmitter (Tx) PIC and a receiver (Rx) PIC onto a single chip. An ideal Tx in this framework is expected to operate across a broad bandwidth, be compatible with CMOS drivers, handle substantial data capacity, emit high optical power, have minimal insertion loss, and be compact.

The proposed Tx PIC architecture features a dual-polarization in-phase quadrature (DP-IQ) modulator [5,6] and a III-V-on-LN laser [9]. The DP-IQ modulator offers advanced modulation capabilities and polarization multiplexing, promising to maximize the reach-capacity product and minimize power consumption while reducing the number of parallel EO interfaces. This approach leads to higher capacity and lower cost per bit. Effective polarization multiplexing requires a low-loss, low-polarization-crosstalk, and wide-wavelength-operation on-chip polarization rotator (PRC), alongside high-performance coherent modulators. Previously demonstrated PRCs showed promising results, with a polarization extinction ratio of ≥20 dB and low insertion loss of <0.3 dB across the entire C band [6]. In [6], we also introduced the first TFLN dual-polarization in-phase quadrature (DP-IQ) modulator, notable for its sub-1-V driving voltage and expansive 110-GHz bandwidth. However, due to the reasonable modulation efficiency of LN (approximately 2 V·cm), the typical modulation length required for CMOS compatibility is nearly 2 cm, a size that is impractical for modern transceiver modules like the Small Form-factor Pluggable and Quad Small Form-factor Pluggable. The introduction of slow-light and ring-assisted Mach-Zehnder modulators on TFLN significantly improves modulation efficiency to 1.29 V·cm [13] and 0.35 V·cm [14], while reducing the footprint to just a few millimeters. Notably, these configurations maintain bandwidth and voltage integrity. Yet, the working wavelength bandwidth remains a crucial factor, especially for long-haul transmission. Traveling-wave modulators with folded optical waveguides and coplanar waveguides offer a promising alternative. Our latest DP-IQ modulator adopts a folded architecture and air-bridge structures, achieving a low driving voltage of

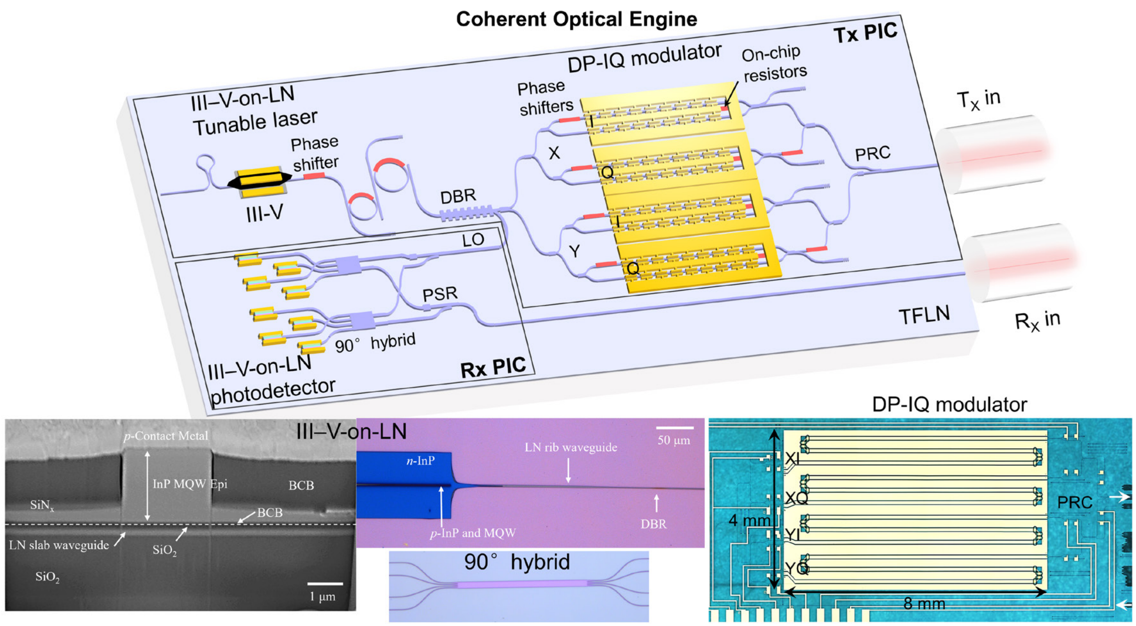

Fig. 1 Conceptual architecture of the TFLN-based coherent optical engine, and our recent works on III-V-on-LN laser and photodetector [9], coherent modulator [5], and 90° hybrid [7] for coherent receivers. PRC, polarization rotator and combiner; PSR, polarization splitter and rotator; DBR, distributed Bragg reflector; LO, local oscillator.

just 1V, a bandwidth exceeding 67 GHz, and a compact footprint of 4 × 8 mm².

Recently, promising avenues for creating light sources suitable for telecommunications have emerged, specifically through erbium-doped LN [15] and the heterogeneous integration of III-V gain materials on TFLN [9-11, 16,17]. Here, we propose the use of III-V-on-LN integration in the conceptual Tx, eliminating the need for an external pump laser. As depicted in Figure 1, light generated from the patterned III-V gain material is coupled into LN waveguides via a vertical adiabatic coupler. Additionally, a TFLN Vernier filter, consisting of two microrings with slightly differing radii, is incorporated into the Fabry-Perot cavity to select the lasing wavelength [9-11]. The primary challenge in this approach lies in achieving low-loss coupling between the III-V and LN materials, ensuring sufficient output power to maintain an adequate signal-to-noise ratio (SNR) during transmission, and attaining a low pump threshold current. Recent advancements in wafer bonding technology [11] and transfer printing technology [16, 17] have demonstrated reliable III-V-on-LN integration. Wafer bonding offers the advantages of wafer-level productivity and precise alignment, whereas transfer printing is cost-effective. Both technologies show promising potential for co-integrating photodetectors and amplifiers on the TFLN PIC.

In our proposed optical coherent receiver design, the modulated optical signals carrying two polarizations are directed to a polarization splitter and rotator (PSR). This PSR is functionally the inverse of the PRC used in the DP-IQ modulator. A portion of the light from the laser in Tx serves as the optical local oscillator (LO), which is then routed to another PSR and divided into transverse electric (TE) and transverse magnetic (TM) polarizations, as the demodulated polarization of the signals. The TFLN Multimode Interference-based 90° hybrid, which we have previously presented in [18], plays a crucial role in the coherent transceiver. Detection is achieved through a four-pair balanced III-V-on-LN photodetector, which produces the in-phase and quadrature components for both TE and TM polarizations. The III-V/TFLN-based photodetectors, employing the same wafer-bonding technology we have already discussed, have been demonstrated in [11]. This shared fabrication process between the Rx and Tx PICs not only streamlines production but also suggests that full integration of these components onto a single chip is feasible, potentially leading to cost reductions.

3. Transmission performance

Leveraging a 100-GHz and 1-V DP-IQ modulator, we have successfully executed a back-to-back coherent transmission utilizing 130 Gbaud probabilistic constellation shaping (PCS) with 400QAM [6]. The measured constellation from this transmission is shown in Figure 2 (a). The DP-IQ modulator enabled us to achieve a groundbreaking single-wavelength net data rate of 1.96 Tb/s and low electrical power consumption of 1.04 fJ/bit. This terabit-per-second transmission greatly benefits from the extensive bandwidth and low fiber-to-fiber loss (< 7 dB), ensuring a robust signal-to-noise ratio (SNR) for higher baud rates and more complex modulation formats. In a related development, S. Almonaci *et al*. utilized a single-polarization IQ modulator, similar in design, to transmit a 260-GBaud QPSK signal at an 800-Gbps net rate over a 100-km fiber. It is noteworthy that this high-symbol-rate transmission was achieved without resorting to nonlinear digital signal processing (DSP) or advanced techniques for mitigating inter-symbol interference. This highlights the potential of these modulator designs in pushing the boundaries of ultra-high-baud-rate short-reach optical transmission capabilities without complex DSP.

In showcasing the long-haul transmission capabilities of the new-generation DP-IQ, we present driverless 703 Gb/s/λ line-rate transmissions, with a subcarrier modulation scheme, over a 1120 km single-mode fiber link. (Fig. 2 (b)) [5]. The demonstrated DP-IQ modulators in the optical links not only meet criteria for compact size and extensive reach-capacity product but also excel in ultra-low power consumption. However, challenges remain in reducing the cost per bit. This objective introduces a few issues, including the need for larger commercially available wafer sizes and improvements in mass production yields.

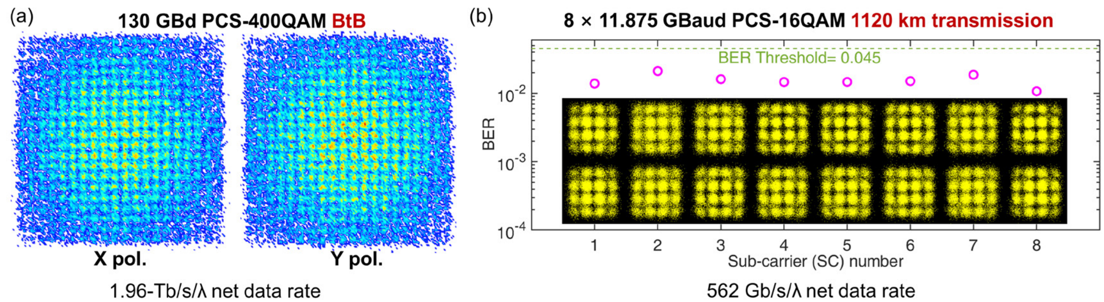

Fig. 2 Experimental results employed our TFLN DP-IQ modulators for (a) 130 Gbaud PCS-400QAM back-to-back transmission [6] and (b) 95 Gbaud PCS-16QAM with 1120-km fiber transmission [5].

4. Conclusion

We review our recent works and the state-of-art developments in TFLN devices and PICs and propose a conceptual optical engine that leverages these technological advancements. The TFLN platform, with its attributes of low optical loss, low power consumption and high data capacity, stands out as a formidable contender for next-generation data communications.

5. References

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