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Dual-polarization thin-film lithium niobate in-phase quadrature modulators for terabit-per-second transmission

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We report, to our knowledge, the first dual-polarization thin-film lithium niobate coherent modulator for next-generation optical links with sub-1-V driving voltage and 110-GHz bandwidth, enabling a record single-wavelength 1.96-Tb/s net data rate with ultrahigh energy efficiency.

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Optical transmission systems need to constantly be scaled to higher capacities to cope with exponential traffic growth. This insatiable demand for capacity drives advances in coherent optical transmission technology, where dual-polarization in-phase quadrature (DP-IQ) modulators are the key components that determine the transmitter bandwidth and port density. By 2027, per-lane interface rates are expected to reach 1.6 Tb/s with both high spectral efficiency and low power consumption [1]. However, maintaining low power consumption and signal-to-noise ratio (SNR) at such a high data rate is extremely challenging. Compact DP-IQ modulators have been demonstrated in silicon-on-insulator (SOI) [2] and indium phosphide (InP) platforms [3]. While the SOI DP-IQ modulator features high-quality manufacturing technology and small size, achieving a half-wave voltage (V_π) of <2 V and scaling the bandwidth beyond 100 GHz are difficult. Moreover, the DP-IQ modulator is expected to operate in the linear region, especially for high-order quadrature amplitude modulation (QAM), whereas the modulation mechanisms of InP and silicon are nonlinear.

Thin-film lithium niobate (TFLN) modulators with linear electro-optic (EO) performance are emerging as next-generation EO modulators with outstanding voltage–bandwidth performance, compact footprint, and low optical loss [4–8]. Here, we report the first DP-IQ in TFLN exhibiting a record single-carrier net bitrate of 1.96 Tb/s with a sub-1-V driving voltage. A polarization rotator and combiner (PRC) is monolithically integrated with four Mach–Zehnder modulators (MZMs) for polarization

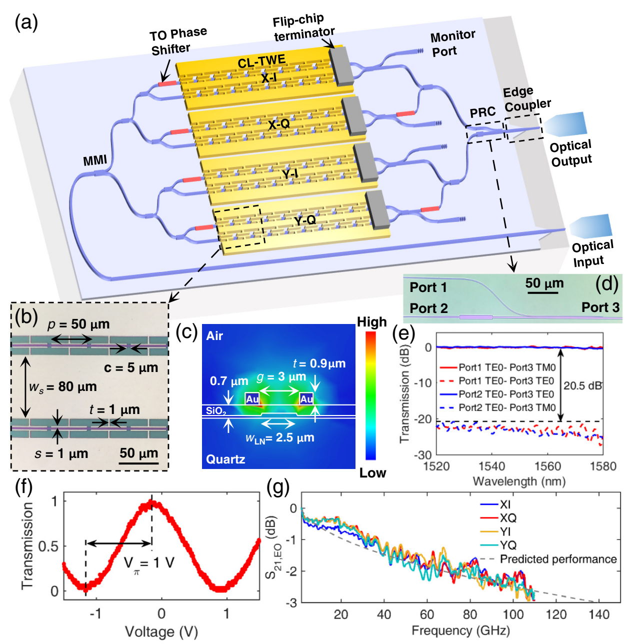

Fig. 1. TFLN-based DP-IQ modulator. (a) 3D schematic of the DP-IQ with a 23.5-mm modulation length. (b) Design of the CL-TWE. (c) Design and microwave field distribution of the modulation region. (d) Microscope image of the PRC. (e) Measured transmission of the PRC. (f) Measured V_π. (g) Measured EO response (1.5-GHz reference).

multiplexing. All of the MZMs exhibit a 1-V V_π and 110-GHz 3-dB EO bandwidth.

Figure 1(a) shows the 3D schematic of the TFLN DP-IQ modulator. The device was fabricated on an x-cut TFLN consisting of a 360-nm-thick device layer and a 500-μm-thick quartz substrate. The DP-IQ is composed of twin-IQ modulators, and each IQ modulator has two parallel sub-MZMs with optimized capacitance-loaded traveling-wave electrodes (CL-TWEs) [Fig. 1(b)]. Here, the CL-TWEs are optimized for low microwave attenuation (simulated 0.21 dB cm^{-1} $GHz^{-1/2}$), as well as perfect velocity matching. Flip-chip bonded 50−Ω terminators were employed at the end of each CL-TWE. The LN waveguides in the modulation region have a top width w of 2.5 μm, slab thickness of 180 nm, and rib height of 180 nm. The 0.9-μm-thick CL-TWE was fabricated on a 0.7-μm- thick SiO_2 cladding. These designs enable low propagation optical loss, high modulation efficiency (simulated result of 2.4 Vcm), and a large tolerance of alignment error between electrodes and waveguides [Fig. 1(c)]. The PRC combines and converts the TE_0 (port1)/TE_0 (port2) polarization modes onto two mutually orthogonal polarization modes in the optical fiber (TE_0/TM_0 in port3) [Fig. 1(d)]. The PRC features a high polarization extinction ratio of ≥20.5 dB and low insertion loss of <0.3 dB over the entire C band [Fig. 1(e)]. Polarization-independent edge couplers were fabricated for efficient coupling with lensed fibers (measuring 1.9 dB/facet). The total fiber-to-fiber loss was measured as 6.8 dB.

The lengths of the CL-TWEs (23.5 mm) were designed for a CMOS-compatible drive voltage and ultrahigh bandwidth. We obtained a V_π value of 1 V [Fig. 1(f)] for all sub-MZMs. All sub-MZMs exhibited an extinction ratio of >20 dB. Figure 1(g) shows the measured small-signal EO response of the device, showing an ultrahigh 3-dB bandwidth of >110 GHz for all channels, which was measured using a 100-GHz photodetector and vector network analyzer with frequency converters (Rohde & Schwarz ZNA). We extrapolated the EO response by fitting the measured electrical response with a theoretical model [dashed line in Fig. 1(g)], which indicates that the 3-dB bandwidth is beyond 140 GHz. We have fabricated more than five DP-IQ modulators on the same chip. All of the devices exhibit bandwidth of 110 GHz, V_π of 1 V, optical loss of 6.5 dB ± 0.5 dB, and extinction ratio of >20 dB. Compared with the work in [6], the present device exhibits better bandwidth performance and more than 20% improvement in V_π.

Figure 2(a) shows a schematic of the transmission setup. Electrical signals are generated by SiGe digital-to-analog converters overclocked to operate at 130 GSa/s [9]. The actual peak-to-peak voltage applied to the sub-MZMs was as low as 628 mV, given the losses from microwave cables and probe array. The root-mean-square voltage was 161 mV. The optical spectrum of the modulated signal is shown in Fig. 2(b). The transmitter and

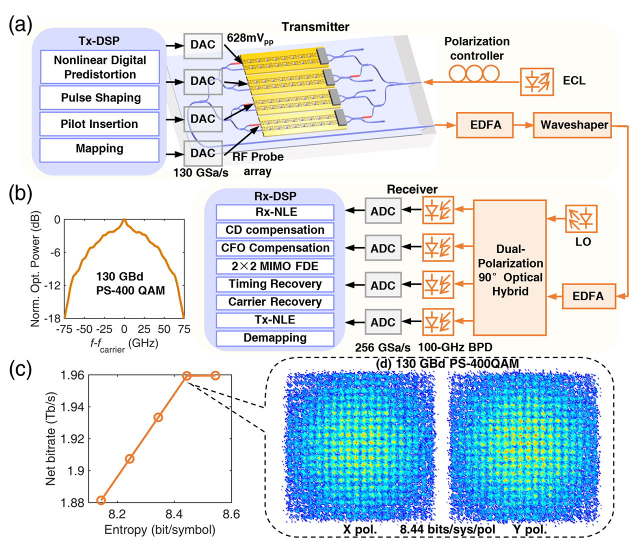

Fig. 2. Experimental results from the 130-Gbaud probabilistic constellation shaping 400 QAM. (a) Experimental setup. (b) Optical spectrum before the wave shaper. (c) Net bitrate as a function of entropy. (d) Constellations with an entropy of 8.44 bit/symbol/pol.

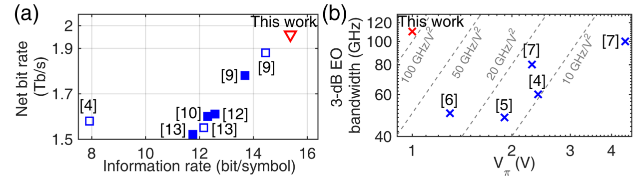

Fig. 3. (a) Records on single-carrier coherent transmission exceeding 1.5 Tb/s. (b) Comparison of voltage–bandwidth performance on TFLN.

receiver digital signal processing (DSP) stack is shown in Fig. 2(a). The DSP makes use of advanced and fully adaptive nonlinear component equalizers, similar to what was used in [9,10]. We select probabilistic constellation shaping (PCS-) 400QAM with entropy between 8.14 and 8.54 bit/symbol/pol [Fig. 2(c)]. The net bit rates reported are obtained using a set of practical spatially coupled convolution low-density parity-check codes with similar forward error correction (FEC) margins as proposed in [11]. With an entropy of 8.44 bit/symbol/pol, we achieved a pre-FEC bit error rate of 1.91×10^{-2}. The measured constellation is shown in Fig. 2(d) with a SNR of 23.4 dB. Using the 10% FEC code, we obtained the highest net bitrate of 1.96 Tb/s/λ ever reported in the literature [4,9,10,12,13], resulting in the highest information rate of 15.38 bit/symbol [Fig. 3(a)].

In conclusion, we have demonstrated the first DP-IQ modulator on a TFLN platform, with the best voltage–bandwidth performance and significantly higher performance than others on this popular EO platform [Fig. 3(b)]. Our ultrahigh-bandwidth and CMOS-level-voltage DP-IQ modulator allows for a record net bitrate of up to 1.96 Tb/s with ultralow power consumption per bit (1.04 fJ/bit). The reported TFLN-based DP-IQ is highly desirable for next-generation EO interfaces operating at ultrahigh speed and low power.

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Data availability. Data may be obtained from the authors upon reasonable request.

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