Driverless 400-Gbps/λ PS-PAM16 Transmission Using Packaged 60-GHz Thin-Film LiNbO3 Modulator with 16-fJ/bit Energy Efficiency

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Abstract We experimentally demonstrated line rate 300-Gb/s PAM4 and 400-Gb/s probabilistically shaped (PS)-PAM16 transmission using packaged thin-film LiNbO3 modulators with only 550-mVpp driving voltage requiring no radio-frequency (RF) amplifiers. Net 296-Gbit/s PS-PAM16 transmission is achieved using 60-GHz transceivers with only 15.5-fJ/bit energy efficiency. © 2023 The Author(s)

Introduction
Along with the recent popularization of new-generation information technologies such as big data, artificial intelligence, cloud computing, and 5G communications, the traffic in data centers is exploding and driving the need to double the Ethernet switch every two years [1]. The optical interconnects are important infrastructures to support high-capacity requirements. The next generation switching silicon supporting 51.2 Tb/s calls for an optical interface at 800G/1.6T and even beyond per module. Therefore, 800G MAC-layer standardization is being studied by IEEE 802.3. Beyond 400 Gb/s Ethernet Study Group [2], which could be based on 8×100 or 4×200 Gbit/s PAM-4 optical links. To support the 1.6T optical interface, highly parallel transmission links are necessitated. Therefore, the low-complexity intensity modulation and direct detection (IMDD) systems are preferred compared to the coherent ones since the receivers of IMDD systems are simpler and free of narrow-linewidth lasers. Benefiting from the compatibility of the complementary metal oxide semiconductor (CMOS) manufacturing, Intel in 2020 demonstrated the first 1.6-Tbps silicon photonics integrated circuit for co-packaged network switch applications, which is based on 16×106.25-Gbps pulse-amplitude-modulation (PAM)-4 optical transmit channels [3]. However, with so many parallel optical channels, sophisticated wavelength management is indispensable. Therefore, a higher-speed transmission link would be a preferable solution for future 800GE and 1.6 TE transceivers. Various high-speed optical transmitters for IMDD systems with 200-Gbit/s have been reported such as directly modulated laser (DML) [4], and electro-absorption modulated laser (EML) [5]. To drive the transmitters, high-bandwidth electrical amplifiers with high output power are needed, which will increase the system cost. On the other hand, LN-on-insulator (LNOI) has emerged as an attractive platform for compact and high-performance devices [6]. The LNOI-based Mach–Zehnder modulators (MZMs) with remarkable electrical bandwidth, low Vrr, and low drive voltage outperform the conventional counterparts and are a promising candidate for next-generation optical interconnects. However, high-speed IMDD experiments using the LNOI-based MZM modulator are nearly all based on chip-level measurements [6-8]. The only one high-speed report based on packaged LiNbO3 modulator achieves 136-Gbaud PAM8 transmission using a 70-GHz oscilloscope [9].

In this paper, we experimentally demonstrated data rate 300-Gb/s PAM4 and 400-Gb/s PS-PAM16 transmission using a 59-GHz oscilloscope and a packaged LiNbO3 modulator without the high-bandwidth electrical amplifiers. The peak-to-peak voltage for both PAM4 and PS-PAM16 modulation is only 550 mV, which is within the AWG output swing. Using the simple feedforward equalizer (FFE), a net 296-Gbit/s PS-PAM16 transmission link is achieved with an energy efficiency of only 15.5 fJ/bit. Compared with [9], the electrical spectral efficiency is improved by 11%. The demonstrated IMDD transmission link using packaged LiNbO3 modulator would be a promising candidate for 800GE and 1.6TE.

Experimental setup
To evaluate the transmission performance of PAM4 and PS-PAM16, the system-level experiment setup is shown in Fig. 1. At the transmitter side, a 256-GSa/s arbitrary waveform generator (AWG) having 65-GHz electrical bandwidth is utilized to generate the baseband Nyquist signal. The distributed feedback (DFB) laser source is with 12-dBm output. The lasing
wavelength of the DFB laser is 1550.4 nm. The LiNbO3 intensity modulator is employed to encode the information on the optical carrier. The LiNbO3 intensity modulator chip is packaged as shown in the inset (i) of Fig. 1. The packaged LiNbO3 intensity modulator is operated at the quadrature point with 1.2-V direct current bias voltage. The insertion loss of the packaged LiNbO3 MZM modulator is 9 dB. The signal is tested at back-to-back (BtB) and after 200-m optical fiber transmission. As the utilized 60-GHz photodiode at the receiver is without the electrical trans-impedance amplifier, the EDFA is deployed at the transmitter to raise the input optical power of the photodiode. The EDFA could be avoided by using high-power DFB lasers. The obtained electrical outputs are digitized by using a 256-GSa/s time-domain oscilloscope with 59-GHz bandwidth. Inset (ii) shows the frequency response of the whole system. The 3-dB bandwidth of the whole system is 47.6 GHz.

In the transmitter-side digital signal processing (DSP), the generated PAM4/PS-PAM signals are pulse shaped by using the root-raised cosine (RRC) filter with a roll-off factor of 0.01. After resampled to fit into the AWG sampling rate, the generated signal is clipped to suppress the peak-to-power ratio (PAPR) for fully utilizing the dynamic range of the AWG. The baud rate of the PS-PAM signal is fixed at 120 Gbaud. The data rate of the PS-PAM signal is varied by tuning the loaded entropy of the PS-PAM signal. The output optical spectrum of the LiNbO3 MZM modulator is presented in inset (iii) of Fig. 1 at different baud rates. At the receiver-side DSP, the signal is lowpass filtered to remove the out-of-band noise and then resampled to 2 samples per symbol for synchronization and channel equalization. We use a linear FFE or decision feedback equalizer (DFE) for channel equalization. The maximum likelihood sequence estimation (MLSE) is only utilized for PAM4 transmission to compensate for the bandwidth-limitation-induced inter-symbol interference (ISI). The transmission performance is evaluated under the metric of bit error ratio (BER) for PAM4 and normalized generalized mutual information (NGMI) [10] for PS-PAM. As the LiNbO3 MZM modulator features low drive voltage, the AWG output swing is swept for both 100-Gbaud PAM4 and 140-Gbaud OOK transmission as illustrated in inset (iv). Therefore, the optimal peak-to-peak voltage is 550 mV for experiments, which is within the AWG output swing and fixed for subsequent tests.

**Results and discussions**

We first evaluate the PAM4 transmission performance at different data rates as presented in Fig. 3. Several forward error correction (FEC) thresholds are employed for performance comparison. With FFE, 250- and 255-Gb/s PAM4 transmission is achieved below 7% and 20% HD-FEC thresholds, respectively. The filter length of the FFE equalizer is optimized for different baud rates. To further improve the performance, a nonlinear DFE equalizer with 10 feedback taps is employed for various data rates. At 7% and 20% HD-FEC thresholds, the maximal transmission...
data rate is 260 and 270 Gb/s, respectively. Since the 3-dB bandwidth of the whole transmission system is around 50 GHz, the bandwidth-limitation-induced ISI becomes strong when the baud rate increases. With 16-tap MLSE (namely, MLSE with a memory length of 2), 300 Gb/s PAM4 is achieved below the 20% HD-FEC threshold. Insets (i-viii) in Fig. 3 show the eye diagrams of PAM4 before/after channel equalization. Due to the bandwidth limitation effect, the eye becomes closed and roughly shows a duobinary feature beyond 100 Gbaud.

Fig. 4 presents the PS-PAM performance also at BtB and 200m transmission. To reduce the implementation complexity for multi-level modulation formats, only the typical FFE is deployed for PS-PAM transmission. Below the NGMI threshold of 0.8 [11], the maximal PS-PAM transmission rate for BtB and 200m using simple FFE is 420 and 405 Gbit/s (net 316.5 and 301.5 Gbit/s), respectively. The NGMI performance of 400-Gb/s PS-PAM signal (net 296 Gbit/s) under different received optical power is evaluated in Fig. 4(b). Insets (i-ii) of Fig. 4 present the eye diagrams of PS-PAM16 at BtB and 200m. Table 1 summarizes the power consumption of the transmission link. The energy efficiency of 400-Gb/s PS-PAM transmission is 15.5 fJ/bit.

Table 1 Summary of LiNbO3-modulator power consumption for 400-Gb/s PS-PAM transmission

<table>
<thead>
<tr>
<th>DC power</th>
<th>RF power</th>
<th>Net rate</th>
<th>E/bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4 mW</td>
<td>0.18 mW</td>
<td>296 Gb/s</td>
<td>15.5 fJ</td>
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</tbody>
</table>

Conclusions
We have demonstrated 300-Gbit/s PAM4 and 400-Gbit/s PS-PAM16-based transmission links using the packaged LiNbO3 intensity modulator. The peak-to-peak voltage for both PAM4 and PAM16 is only 550 mV within the AWG output swing. The NGMI performance of the 400-Gb/s PS-PAM16 transmission achieves a net rate of 296 Gbit/s with only 15.5-fJ/bit energy efficiency. This work could pave the way toward 800GbE and 1.6TbE standardization.

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References


