

Net 556.8 Gbps/pol Coherent Transmission Enabled by a Two-segment All-Silicon Modulator

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Abstract We experimentally demonstrate optical coherent transmission with a segmented all-silicon modulator. Utilizing two segments, we realize 124GB-16QAM, 120GB-32QAM and 116GB-64QAM, enabling a maximum 556.8 Gbps/polarization net line rate.

Introduction

High symbol rate transmission is key to meet sustained increasing demand for transmission capacity^[1]. Transmission at symbol rates beyond 100 GB has been widely reported, leading to net line rates as high as 1.58 Tbps for single carrier transmission^[2]. Wide-bandwidth modulators are essential for such transmissions. In particular, silicon photonics (SiP) modulators have drawn considerable interest in the telecommunications industry. Experimental demonstrations by using SiP modulator have witnessed increasing symbol rates, such as 1 Tbps in 100 Gbaud 32 QAM^[3], and more recently, net 1 Tbps data rate in 105 GB 64QAM^[4], i.e., 500 Gbps/polarization.

We further improve the transmission capacity by using a dual, equal-length segmented all-silicon modulator. We take advantage of the extremely wide bandwidth (>60 GHz) of the modulator to achieve 116 GB 64QAM on a single polarization, We push the net data rate to 556.8 Gbps per polarization on a single carrier.

Modulator Characterization

We recently reported the design, fabrication and characterization of a wide-bandwidth SiP segmented modulator; details can be found in^[5]. The device is an IQ Mach-Zehnder modulator (MZM) modulator with travelling electrodes. The MZM has three segments, each 2 mm long. Some important parameters are listed in Tab. 1. The E-O bandwidths measured on different segments were similar.

We use two out of three segments for the transmission experiments reported, which yielding a total 4 mm MZM phase shifter length. We use 2 V bias for each segment in both in-phase and quadrature (I/Q) MZM branches to avoid forward bias on the PN junction when applying an radio

frequency (RF) signal.

Tab. 1: SiP Modulator characterization

	Value	Unit
Segment number	3	–
Length/seg.	2	mm
3-dB BW @0V DC	34	GHz
3-dB BW @2V DC	63	GHz
3-dB BW @4V DC	> 67	GHz
V_{π} w/ 1seg	>12	V
V_{π} w/ 2seg	9	V
V_{π} w/ 3seg	5.5	V

Transmission and Results

We tested the SiP segmented modulator in coherent optical transmission with a single polarization and in a back-to-back scenario. The experimental setup is shown in Fig. 1, with offline digital signal processing (DSP) processing at both transmitter and receiver. We use a digital-to-analog converter (DAC) (Micram DAC5, 128 Gsamples/sec) to generate four RF signals for the segmented modulator input. An RF amplifier (SHF S804, 24 dB gain, 16 dBm output) drives the DAC output to about 2.8 V peak-to-peak RF swing, and is fed to the chip via a GSSG probe. Identical symbols are loaded to the two segments; we use an RF phase shifter to carefully align the signals on each segment to coincide in time.

An external cavity laser (ECL) at 1548 nm with 100 kHz linewidth is boosted by a high power erbium doped fiber amplifier (EDFA) (EDFA1 in Fig. 1). We control modulator input power via the EDFA to simulate different optical signal-to-noise ratio (OSNR) conditions, with a maximum OSNR of 26 dB. After the SiP modulator, a two-stage EDFA compensates high loss from the silicon device. An optical filter (Finisar Waveshaper) between the two EDFAs removes out-band amplified spontaneous noise (ASE) noise; it has a rectan-

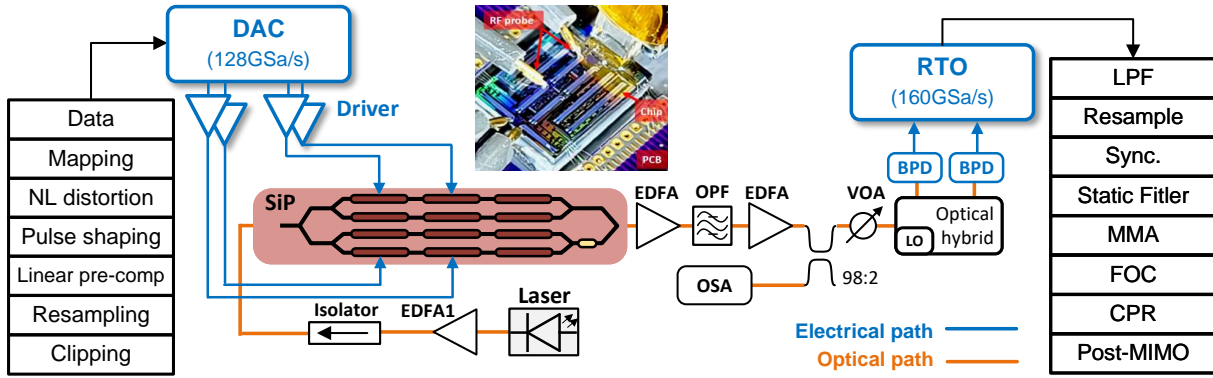


Fig. 1: Block diagram of experimental set-up and TX/RX DSP

gular shape with 2 nm width. No optical compensation for bandwidth is applied, i.e., no filter shaping. We monitor the signal spectrum and OSNR with an optical spectrum analyzer (OSA) via a 98:2 optical coupler.

We use the variable optical attenuator (VOA) before the optical hybrid to fix received optical power at 4 dBm. A 70 GHz bandwidth balanced photodetector (BPD) converts the signal to the electrical domain and is captured by a real-time oscilloscope (RTO) with 160 Gsamples/sec and 63 GHz cut-off frequency (Keysight DSOZ634A).

We generate a length $2^{18}-1$ pseudorandom binary sequence (PRBS) at the transmitter DSP, and map bits to quadrature amplitude modulation (QAM) symbols. We apply either linear or one of two nonlinear pre-distortions. The first nonlinear pre-distortion is a Volterra^[6] filter with 251, 42 and 14 taps for the first, second and third order kernels, respectively. The second is a Look-up table (LUT)^[7] with symbol lengths of 3 or 5, denoted LUT3 and LUT5, respectively. Linear pre-compensation is a finite impulse response (FIR) filter with 125 taps combating the bandwidth limitation of the DAC and driver and excludes the modulator roll-off; modulator roll-off is addressed in receiver DSP.

At the receiver DSP, we apply a tenth order super Gaussian low pass digital filter. We resample to two samples per symbol and apply a 2×2 static multiple-input multiple-output (MIMO) filter and another multi-modulus algorithm (MMA) with least mean square (LMS) updates. The static filter with 133 taps compensates all the bandwidth filtering effects from SiP modulator, BPD and the RTO. We use a MMA with 65 taps to equalize residual intersymbol interference (ISI). After frequency offset compensation (FOC) and carrier phase recovery (CPR), we estimate bit error rate (BER) performance over at least two PRBS.

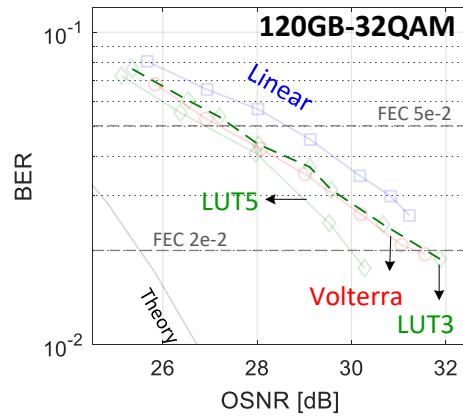


Fig. 2: Nonlinear pre-distortion comparison

In Fig. 2 we report the BER for 120 GB 32QAM using various pre-distortion methods. The plot includes a theoretical BER curve and two forward error correction (FEC) thresholds: 20% FEC at BER $2e-2$ and 25% FEC at BER $5e-2$. We tested linear pre-compensation (squares), Volterra filter (circles), and LUT3 and LUT5 (diamonds). Nonlinear pre-distortion always outperforms linear pre-distortion. The LUT3 and Volterra had very similar performance across the entire OSNR range, with BER falling below the 20% FEC (BER $2e-2$) at around 32 dB OSNR. The LUT5 offers the best performance, and only requires about 30.5 dB OSNR for 20% FEC threshold. At low OSNR regime the LUT5 advantage is marginal, as we have insufficient noise averaging for good LUT estimation.

We next examined three QAM orders: 16, 32 and 64. Roughly speaking, good complexity/performance trade-offs were obtained with linear for 16QAM, LUT3 for 32QAM and LUT5 for 64QAM, hence we present results only for these cases to save space. In Fig. 3(a) we sweep the symbol rates from 100 to 124 GB. The BER of 16QAM stays below the 7% FEC (BER $3.8e-3$) up to 116 GB, and then stays below the 20% FEC threshold. For 32QAM a 20% FEC is needed up

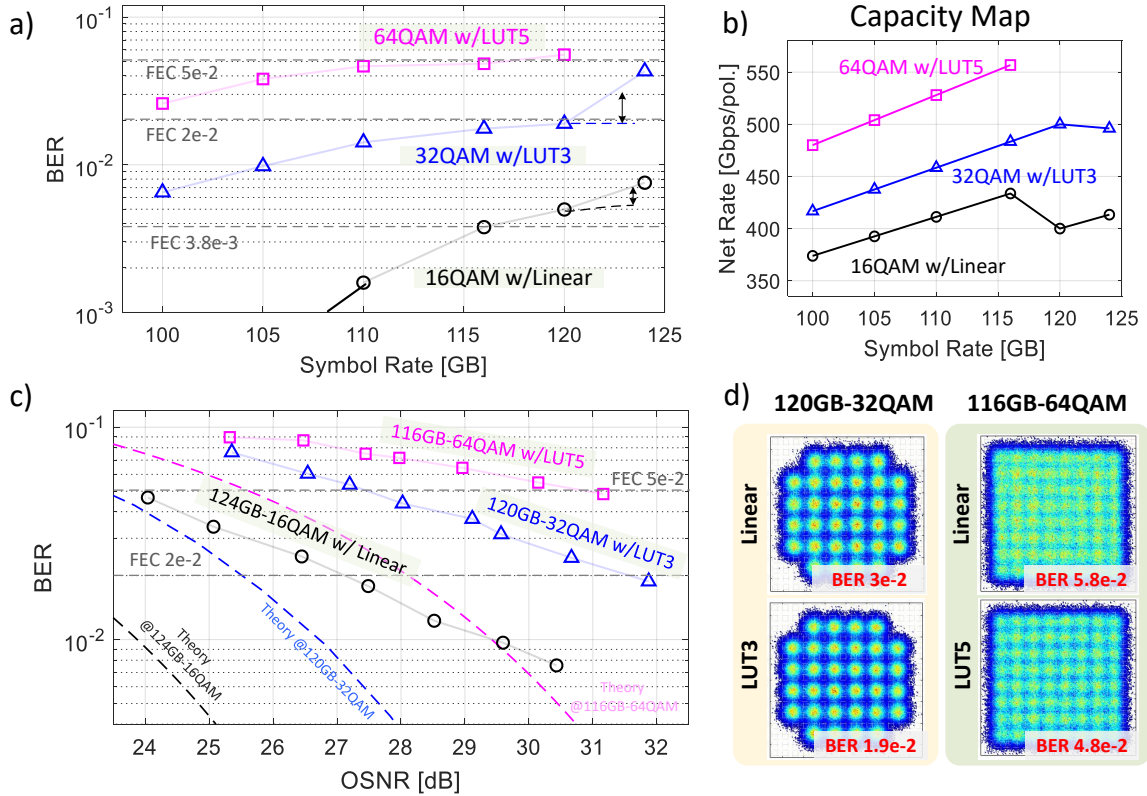


Fig. 3: 16, 32 and 64QAM transmission results with different pre-distortion techniques: (a) symbol rate sweep; (b) corresponding net line rate; (c) OSNR versus BER on 124GB-16QAM, 120GB-32QAM and 116GB-64QAM: and (d) constellations at maximum OSNR of 120GB-32QAM and 116GB-64QAM with linear and nonlinear pre-distortion.

to 120 GB. For 64QAM a 25% FEC is needed up to 115 GB. All curves show a sharp increase in BER when moving from 120 to 124 GB. This limitation is from the RTO, as we approach its cut-off frequency (63 GHz), and is not attributable to the SiP MZM.

Figure 3(b) gives net line rate estimated from BER results in Fig. 3(a) and the corresponding FEC threshold. We achieved net 500 Gbps/pol with 105 GB 64QAM (25% FEC), as well as 120 GB 32QAM (20% FEC). We achieve a maximum at 556.8 Gbps/pol net rate with 116 GB 64QAM with a 25% FEC overhead.

From Fig. 3(b) the maximum achievable baud rates are 124, 120 and 116 GB for 16, 32 and 64QAM, respectively. In Fig. 3(c) depicts OSNR-BER curves for these cases. Theoretical BER is plotted for reference. We can see required OSNR of 16QAM is 27 dB for a net rate of 413.3 Gbps, and 24 dB for a net rate of 396.8 Gbps. For 32QAM, required OSNR is 31.5 dB for 500 Gbps and 27.5 dB for 480 Gbps. For 64QAM, 31 dB OSNR and higher is required to achieve the 556.8 Gbps net rate.

In Fig. 3(d) we explore the impact of linear vs.

nonlinear pre-distortion. We present constellations at the maximum OSNR, i.e., 31.1 dB for 116GB-64QAM, and 31.8 dB for 120 GB 32QAM. The nonlinear pre-distortion pushes the BER performance below the FEC thresholds in each case.

Conclusion

We demonstrated back-to-back optical QAM transmission up to 124 GB with a dual equal-length segmented SiP modulator. The high bandwidth of the modulator led to us achieving a maximum net line rate at 556.8 Gbps by 116 GB 64QAM on a single polarization. We discussed the performance of several nonlinear pre-distortion techniques. We examined the best trade-off of complexity and performance at each constellation size. We presented BER under various symbol rate and OSNR scenarios.

Acknowledgements

Funded by NSERC (CRDPJ528381); chip fabrication via CMC Microsystems; chip packaging by Simon Levasseur.

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