Silicon Photonics for 100Gbaud

Jianying Zhou[1], Jian Wang[1], and Qun Zhang[2]
[1]NeoPhotonics Corporation, 2911 Zanker Road, San Jose, California 95134, USA
[2]Trafton Science Center N 242, ECET Department, Minnesota State University, Mankato, MN 56001, USA
jianying.zhou@neophotonics.com

Abstract: We reviewed recent breakthroughs on silicon photonic for 100Gbaud operation. We experimentally demonstrated 120Gbaud QPSK and 100Gbaud 32QAM operations using a high performance all-silicon IQ modulator with extinction ratio of >25dB and 6dB-bandwidth of 50GHz.
OCIS codes: (250.4110) Modulator; (250.5300) Photonic integrated circuits; (060.1660) Coherent communications

1. Review of state of the art technologies

The demand for high transmission capacity continues to push research towards increasing channel baud rates for data center and communication applications. 50-69Gbaud (Gbd) operations start in commercial use via advanced modulation formats such as 4-level pulse amplitude modulation (PAM4) for intra-data center connectivity, or 16-64 quadrature amplitude modulation (QAM) for data center interconnect (DCI), metro, and long haul applications [1]. Moreover, 96Gbd 32QAM and 120Gbd 16QAM gain interest for single carrier net rate 800Gb/s DCI applications in OIF forum. QPSK and low order QAM operating at 100Gbd and beyond are attractive for maximum transmission reach with a given capacity per single wavelength carrier for next generation metro and long haul applications [2].

Two material platforms, indium phosphide (InP) and silicon photonics (SiPho), have been used to fabricate photonic integrated circuits (PICs) for optical transceivers. Although InP achieves higher performance for modulation [2], SiPho enables more compact and cost-efficient optical transceivers benefitting from high-yield photonic and photonic-electronic integration by leveraging fabless CMOS process, high reliability, and low cost mass production [3-6]. Furthermore, SiPho provides a straightforward path to higher levels of integration by combining the receiver with the modulator in a monolithic integrated transceiver PIC. These enable coherent transceivers for single carrier high capacity DCI applications, where high baud rate high order QAM modulation can be used to achieve low cost per bit with high spectral efficiency [1, 5, 6].

Ge photo detectors have attained 100Gbps RZ data reception with 67GHz 3dB opto-electrical (OE) bandwidth (BW) [7] and are commercially available for high baud rate applications with 50GHz 3dB OE BW in process design kits (PDK) from silicon open foundries [8]. Therefore, the modulator electro-optic (EO) BW must be enhanced to enable high baud rate operation. In a coherent transceiver, a complex nested modulator composed of four child Mach-Zehnder modulators (MZMs) is used to realize high baud rate high order QAM with the stringent requirements on EO response [9] and DC extinction ratio (ER) [1, 5]. In recent years, modulators based on InP material [2] and silicon based hybrid materials such as organic [3] or plasmonic [4] have been demonstrated to operate at 100-Gbd and beyond. But with all-silicon material, carrier depletion MZM may be the most cost-efficient for commercial use. One major challenge is to achieve efficient high speed EO modulation [3-6]. Recently, 100Gbd 32QAM was reported with an all-silicon modulator by using a combination of optical and digital filtering combined with nonlinear compensation techniques [6]. More recently, we demonstrated an all-silicon carrier depletion modulator, with ER of over 25dB and 6dB EO BW of 50GHz, operating at 120Gbd QPSK and 100Gbd 32QAM [9]. To the best of our knowledge, this is the first time to demonstrate 120Gbd QPSK and 100Gbd 32QAM operation with an all-silicon modulator and linear digital equalization. The latter enables single carrier 1Tb/s gross rate using dual polarization multiplexing. In the next sections, we summarize the design and characterization of the all-silicon modulators and their performances and limitations in coherent transceivers to operate at 100Gbd and beyond.

2. Device model, design and characterizations

The design for a high speed, high performance SiPho modulator involves a number of key elements, such as PN junction, phase shifter, RF traveling waveguide (TW) and termination, which have varying impacts on performances. To design this modulator, we developed a hybrid model utilizing an innovative segmental method, which allows us to combine electromagnetic and circuit models to accurately model distributed characteristics of a SiPho traveling waveguide modulator. The hybrid model achieves the phase match and the impedance match by the optimization of doping, optical and RF design [5].

Figure 1 shows a function block diagram of MZM IQ modulator, modulator EO response and heater phase tuning transfer functions. Each MZM of I or Q comprises two PN phase shifters (PS) to form the MZI structure in a single drive push-pull configuration. The PN junction has a lateral structure in a rib waveguide. Intermediate doping of p+ and n+ is used to reduce the electric contact resistance while avoiding high optical loss from p++ and n++ regions for electrical contacts. RF TW has a simple differential coplanar strip (CPS) structure. The heaters are used for thermal phase tuning of the MZM. The test data shows the dependence of EO BW on doping, PS length and PN bias. The highest 3dB and 6dB EO BW are respectively 44GHz and 62GHz with 2mm PS and mid doping measured at -5V PN bias, but with high V_π of ~8V. To reduce V_π, high doping and low bias are needed. The test data shows that MZM with high doping and 2mm PS has 3-dB and 6-dB EO BW of 28GHz and 49GHz at -2V PN bias, respectively. We designed an IQ modulator, IQ1, using high doping and 1.9mm PS with an estimated optical loss of 5.6dB and a moderate V_π of ~6V, for high baud rate high order QAM applications. We also fabricated the modulator IQ2 by using 3mm long PS and mid doping with lower V_π of ~5V, but less BW, 42GHz 6dB EO BW at -2V PN bias. Figure 1 also shows the measured heater phase tuning transfer function for IQ1 and IQ2, achieving ER>25dB for both child and parent MZMs.

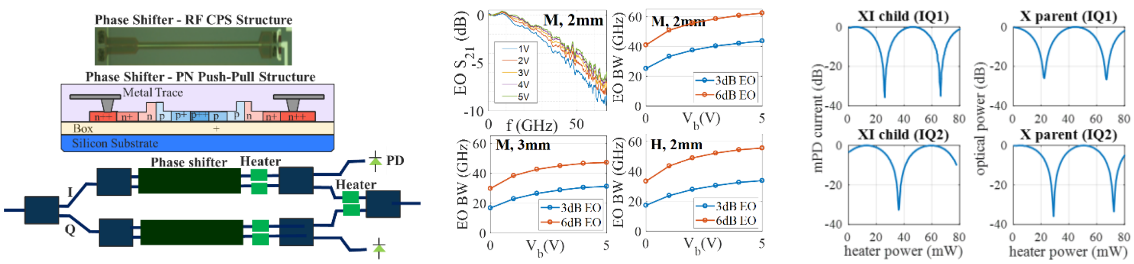

Fig. 1 Function block diagram of MZM IQ modulator (left), modulator EO response (middle) and heater phase tuning transfer functions (right).

3 System performances and limitations

System performances of coherent transceivers with SiPho modulators operating at high baud rate high order QAM are limited mainly by their EO BW, although other factors in transmitter (Tx) components also matter such as digital to analog convertor (DAC) from DSP ASIC, driver, and high frequency interconnect through transmission line in the package and printed circuit board. If the Tx frequency response is post-equalized in receiver (Rx), the noise component may be enhanced. So a pre-equalizer (Pre-EQ) in the Tx must be used to compensate for the attenuation at high frequency in the Tx analog frequency response and mitigate the BW limitation [6, 9]. Most recently, Zhalehpour et.al. have demonstrated 100GBaud 32QAM with an all silicon modulator. However, an optical filter for additional Pre-EQ and nonlinear compensation are used [6]. An optical filter can provide an analog Pre-EQ without introducing digital noise; but it increases the system complexity and may induce a penalty with laser frequency offset. In our demonstration of all-silicon modulators operating at 100Gbd, we only use a linear digital Pre-EQ at the Tx. We show that the transmission performance can be optimized as a tradeoff between signal-to-noise-and-distortion-ratio (SINAD) and BW of compensation under severe BW limitations of SiPho modulators [9].

Figure 2 shows the experimental setup for high baud rate transmission and the measured constellations and optical spectrums with 120Gbd QPSK, 100Gbd 16QAM, 100Gbd 32QAM, and 85Gbd 64QAM. An arbitrary waveform generator (AWG) with 120GSa/s and 45GHz BW and an OMA with 160GSa/s and 63GHz BW are used for test. The Gray-coded QAM symbols are generated with pseudo random binary sequence (PRBS) of order 15. A root-raised-cosine (RRC) filter with roll-off factor of 0.2 is used for pulse shaping. The AWG outputs with linear digital Pre-EQ are applied to the SiPho IQ modulator chip via RF drivers and probes. The all-silicon IQ modulators, IQ1 and IQ2, were used in the test with PN bias of -2V for low V_π. The RF driver has 50GHz 6dB BW. The setup includes a NeoPhotonics laser operating at 193.7THz and an ASE noise loading station for adjusting the optical signal to noise ratio (OSNR). The Rx DSP includes adaptive equalizer, phase recovery, and bit error rate (BER) counting.

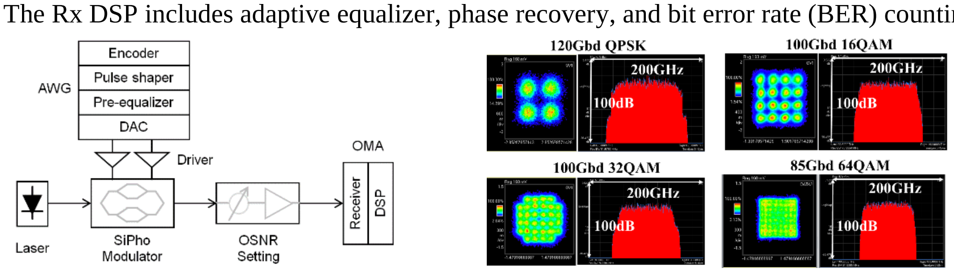

Fig. 2. Experimental setup of QAM transmission with SiPho IQ modulator (left), and the measured constellations and optical spectrums with 120Gbd QPSK, 100Gbd 16QAM, 100Gbd 32QAM, and 85Gbd 64QAM (right).

Figure 3 a) shows BER vs. Pre-EQ BW at 28dB OSNR with 100Gbd 16QAM and 32 QAM, and b) shows BER vs. OSNR with different modulation formats and baud rates using the optimized Pre-EQ BW of 45GHz, in single polarization with modulator IQ1. Test data shows that the OSNR sensitivity is 25.5dB for 120Gbd QPSK, and 26.7dB for 100Gbd 16QAM, both at FEC threshold of 1.25e-2 using 15% OH. For 100Gbd 32QAM, the BER floor is >1.25e-2 due to the use of the high order QAM. A modern soft-decision FEC with convolutional Low-Density Parity-Check codes has been proposed to enable successful operation at extremely high pre FEC BER, achieving a FEC BER threshold at 4.5e-2 with 24% OH [10]. For 32QAM, the OSNR sensitivity is 32dB for 100Gbd, and is 30.5dB for 96Gbd, both at FEC threshold of 4.5e-2 using 24% OH. For 64QAM, maximum baud rate is limited to 85Gbd with BER floor at about 6.5e-2. Figure 3 c) shows BER vs. OSNR at 100Gbd 16QAM and 32QAM with IQ1 and IQ2. For 16QAM, IQ2 has a slightly worse performance compared to IQ1, indicating a BW limitation from IQ2. As shown in Fig. 1, the measured 6dB EO BW is ~50GHz for IQ1 and is ~40GHz for IQ2 at -2V PN bias. For 32QAM, IQ1 and IQ2 have a similar performance. This implies that, for 100Gbd 32QAM, IQ1 and IQ2 may have a common performance limitation, due to a fast roll-off of Tx response above 45GHz including contributions from driver and DAC. Thus the performances can be improved by slowing the roll-off above 45GHz or by an increased ENOB [9], as an alternative to using an optical filter for additional Pre-EQ combined with nonlinear compensation techniques [6].

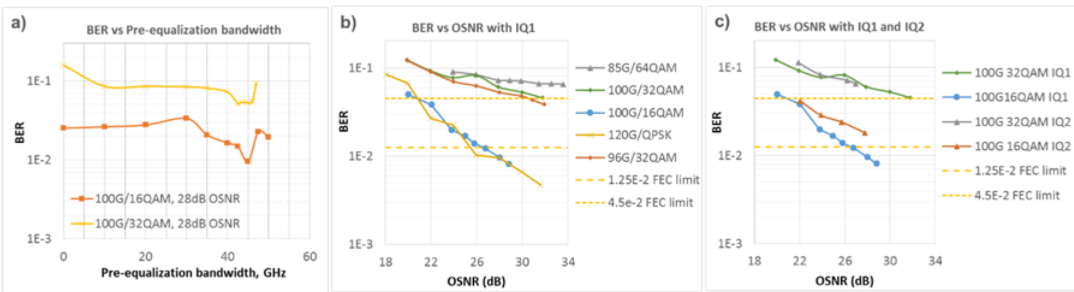

Fig. 3 a) BER vs. Pre-EQ BW at 28dB OSNR for 100Gbd 16QAM/32QAM, b) BER vs. OSNR with different modulation formats and baud rates with optimized Pre-EQ BW of 45GHz, with modulator IQ1, and c) BER vs. OSNR at 100Gbd 16QAM/32QAM with IQ1 and IQ2.

4 Conclusion

Recent breakthroughs in all-silicon modulators promise coherent transceivers operating at 100Gbd 32QAM, which enable single carrier 1Tb/s gross rate using dual polarization multiplexing. We designed and fabricated an all-silicon carrier depletion MZM with 6dB EO BW of 62GHz measured at -5V PN bias. We experimentally demonstrated an all-silicon IQ modulator, with an extinction ratio of >25dB, 6dB-EO BW of 50GHz and moderate V_π of ~6V at -2V PN bias, operating at 120Gbd QPSK and 100Gbd 16QAM with BER below FEC threshold of 1.25e-2 with 15% OH, and 100Gbd 32QAM with BER achieving FEC threshold of 4.5e-2 using a modern FEC with 24% OH. To the best of our knowledge, this is the first time to demonstrate an all-silicon modulator operating at 120Gbd QPSK and 100Gbd 32QAM using practical Nyquist filter and linear digital compensation in commercial AWG and OMA.

5 References

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