High-Baudrate SiP and InP Modulators for Data Center Interconnects

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***Abstract*—The booming internet traffic sets highly challenging requirements for high-speed computing where low latency is required. This leads to a choice of intensity modulation and direct detection system with the highest baudrate possible. Furthermore, record baudrate supporting modulators will be the key technology for future optical interconnect applications. Therefore, we demonstrated silicon photonics and indium phosphide modulators at highest possible sysmbolrate.**

Keywords— Silicon photonics, indium phosphite, on-off keying, pulse amplitude modulation, Data Center interconnects.

I. Introduction

The Data Center links need to scale according to Internet traffic in an energy efficient manner with low latency. For this purpose, optical 0.8 - 1.6 Terabit links based on intensity modulation and direct detection system with highest possible baudrate per lane are desirable [1]. Silicon photonics ring resonator modulator with integrated laser demonstrated 128 Gbaud on off keying [2]. Multichannel integration advantages of SiP RRM have been shown by implementing 4 x 224 Gbps [3]. Also, very high symbol rates have been demonstrated with think film lithium niobate [4] and plasmonic modulators [5]. In this paper, we are going to report on recent advances on high-baudrate modulators in silicon photonics (SiP) and indium phosphide (InP) technologies. We are going to report on SiP ring resonator (RRM) and Mach-Zehnder modulators (MZM) [6], [7] and on InP based externally modulated (EML) and directly modulated lasers (DML) [8], [9]. In case of InP modulators we demonstrate the highest possible symbol rates with monolithically integrated and packaged components without optical amplification.

II. Experimental Setup

Figure 1 shows the experimental setup for testing SiP and InP modulators. The signal bit sequence for on-off keying is generated offline in MATLAB from a random binary sequence of >1 million bit-length obtained using the Mersenne Twister generator with a shuffled seed number. The obtained bit sequence is firstly digitally up-sampled to 4 samples per symbol, pulse-shaped with root-raised-cosine (RRC) filter with different roll-off factor, and down-sampled to 256 GSa/s to match the sampling rate of the arbitrary waveform generator (AWG, prototype of Keysight M8199B). For Fig. 1(a), the output voltage swing of the AWG is set to be 2.7 Vpp for RRM

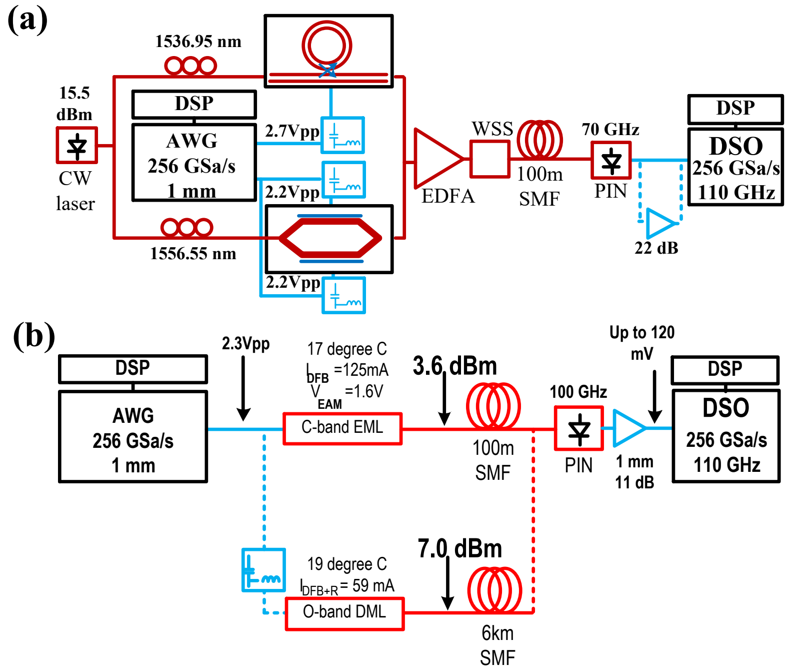

Figure 1. (a) experimental setup for SiP modulators on chips, (b) experimental setup for packaged InP-based modulators.

and 2.2 Vpp per arm for MZM resulting in a total swing of 4.4 Vpp for the differential drive. SiP modulators are reverse biased using 110 GHz bias-tees at 1.15 V. Signal and bias are applied to modulators using 67 GHz RF probes. The output power of the tunable laser is set to +15.5 dBm and coupled into the modulators using grating couplers. For both modulators, at 67 GHz we measure less than 10 dB attenuation. The smooth roll-off in the frequency transfer function makes the usable modulator bandwidth far beyond 67 GHz. For Si MZM tunable laser wavelength is set to 1556.554 nm to ensure lower coupling losses from grating couplers. The heater current is set to 6.65 mA for MZM to set the optimal operation point (4 dB) after optimization. After optimization to determine the best resonance for modulation, Si RRM tunable laser wavelength is set to 1536.947 nm, which corresponds to 7.6 dB detuning. To avoid RRM instability due to self-heating, the heater current is set to 3.6 mA. After optical modulation the signal is transmitted over 100 m of SMF. An Erbium-doped fiber amplifier (EDFA) with an output power of 13 dBm is used to overcome coupling losses. Wavelength selective switch (WSS) is used to filter out the amplified spontaneous emission noise, resulting in up to 6.6 dBm optical power on 70-GHz PIN photodiode (PD), which is used to receive a signal from both modulators. The signal from PD is delivered to a 110-GHz real-time digital storage oscilloscope (DSO, 256 GSa/s, Keysight UXR1104A). For RRM PAM4 transmission a packaged electrical amplifier with a gain of 22 dB is used after PD.

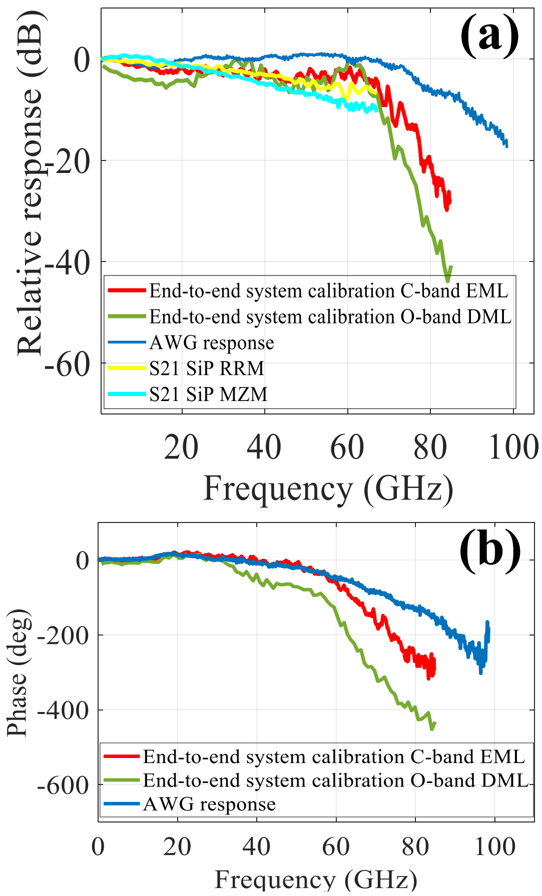

Fig. 2. End-to-end system calibration, modulator and AWG responses.

In Fig.1 (b) the AWG output voltage swing is 2.3 Vpp after embedded electrical amplification. In the case of the C-band EML, the module is directly connected to the AWG output with a 1-mm connector adaptor as can be seen in the inset in Fig.1. For the O-band DML, a 110-GHz bias-tee is used to deliver the laser bias current. A 1-mm connector adaptor is used to connect the bias tee to the output of AWG. Also, as the DML is in the package with a 1.85 mm connector and an adaptor to 1-mm is needed, see the inset in Fig.1. This affects the performance of the DML-based transmitter at a high baudrate. The EML is regulated to operate at 17°C to emit +3.6 dBm optical power after electro- absorption modulation, and the DML is regulated at 19°C and has an output power of +7

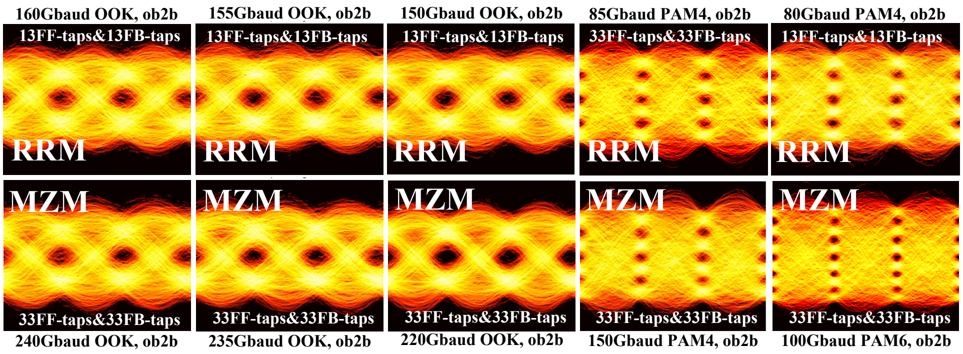

Fig. 3. Eye diagrams for both RRM and MZM.

dBm when biased. The bias currents are shown in Fig.1(b). Due to the different operational bands of the two transmitters varied transmission distances can be achieved, i.e., 100-meter SMF for the C-band EML-based transmitter, and 6-kilometer SMF for the O-band DML-based transmitter. A 100-GHz PIN photodiode is connected to a packaged electrical amplifier of 11 dB gain with a 1-mm adaptor at the receiver. In this configuration, we can deliver up to 120 mV of an electrical signal to a 110-GHz real-time digital storage oscilloscope (DSO, 256 GSa/s, Keysight UXR1104A). Calibrated end-to-end amplitude and phase responses of the EML and DML-based setups without the optical fiber link are shown in Fig. 2. The intrinsic response of the AWG is shown as a reference. We can see that EML and DML-based setups in amplitude experience quite similar performance until 65 GHz. The main difference can be seen in phase response where DML-based setup is different already starting from 30 GHz. Here we clarify that obtained end-to-end amplitude and phase responses of the EML and DML-based setups are not used in digital signal processing routines. We obtain them for visualization purpose. In the paper we rely only on post- equalization. Applying pre-equalization would lead to a limited voltage swing resulting in poor performance of the entire link. Therefore, we decided to skip pre-equalization completely. In addition, we can use post-equalization only thanks to the fact that the 20-dB end-to-end system bandwidth for both setups is above 70 GHz. The signal is processed offline with a matched filter, a timing recovery and down-sampling process based on maximum variance, a symbol-spaced decision-feedback equalizer (DFE) with different feedforward (FF)-tap and feedback (FB)-tap configurations, and the BER is counted.

III. Results and Discussions

We evaluate the performance of both modulators with three modulation formats at a 6.25 % OH HD-FEC threshold of 4.5×10^{-3} for optical back-to-back (ob2b) and after transmission over fiber. Figure 3 shows selected eye diagrams of SiP modulators for ob2b, captured at the highest received optical power. However, Figure 4 shows selected eye diagrams of InP modulators after transmission, captured at the highest received optical power. We have shown highest symbol rates for OOK with all modulators in this work.

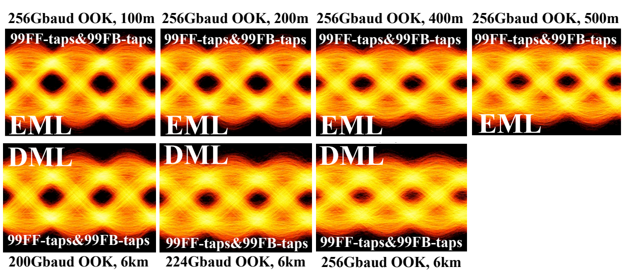

Fig.4. Eye diagrams for on-off keying obtained with InP transmitters.

Acknowledgment

We thank Keysight for hosting the experiment and for loaning the M8199B AWG prototype and the UXR1104A Infiniium UXR-Series Oscilloscope. This work was also supported by the Swedish Research Council (VR) projects 2019-05197 and 2022-04798, the H2020 ICT TWILIGHT Project (No. 781471), the ERDF-funded RINGO project (No. 1.1.1.1/21/A/052), the RTU Science Support Fund, the National Natural Science Foundation of China (U2006217, 61775015), the China Scholarship Council (202107090113), and the National Key Research and Development Program of China (2018YFB1801500).

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