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Abstract *We report on a 116 Gbit/s OOK, 4PAM and 105 Gbit/s 8PAM optical transmitter using InP-based integrated EML for interconnect applications with up to 30 dB static extinction ratio and over 100 GHz 3 dB bandwidth with 2 dB ripple.*

Introduction

The 3rd generation 400G client-side links is demanding a solution as the cloud services together with the huge size datasets are driving demand for bandwidth in datacentres[1,2]. The promising solution is four optical lanes at 100 Gbit/s net rate in order to reduce complexity, size, power consumption and cost. This task becomes even more challenging with silicon and InP opto-electronic components beyond 70 GHz. Advanced modulation formats such as carrierless amplitude phase (CAP) modulation[3], discrete multi-tone (DMT)[4], or pulse amplitude modulation (PAM)[5,6] allows for more efficient bandwidth utilization at the cost of higher digital signal processing (DSP) complexity. Therefore higher bandwidth opto-electronics with simpler modulation formats seems to be the most practical.

After years of research on advance modulations formats[1-6], consensus seems to evolve towards 4PAM[1,2,5,6] and on-off keying (OOK)[7,8], as it saves complexity on the transmitter side. OOK is preferable in terms of power budget and transmitter complexity, as limiting amplifiers and electrical multiplexers technologies up to 120 Gbit/s have already matured into products. However, cost-efficient optical modulators at this bandwidth are not commercially available. PAM may reduce the bandwidth requirements, but it also reduces the receiver sensitivity and significantly complicates the electrical side of the transmitter (i.e. digital to analogue converters (DACs), linear drivers etc.).

In this paper we report on a cost-efficient integrated externally modulated laser (EML) with high bandwidth for 116 Gb/s OOK (the first time achieved on a single EML) and linear enough to accommodate 116 Gbit/s 4PAM and 105 Gbit/s 8PAM, while requiring a driving voltage of 2 Vpp, paving the way for high speed multilevel modulation formats.

Optical Transmitter

The optical transmitter is based on a monolithically integrated distributed feedback laser with traveling-wave electroabsorption modulator (DFB-TWEAM) designed by KTH, fabricated by KTH and Syntune and packaged by u²t Photonics[8]. The absorber is based on the 12 strain-compensated InGaAsP quantum wells/barriers (QWs) of around 9 nm thickness each and the gain section of the DFB based on 7 QWs 7 nm thick grown by metal vapour phase epitaxy coupled with butt-joint technique. Figure 1 shows the power versus current, power versus bias voltage and the frequency response taken at 22º C. As we can see from Fig. 1a the threshold current is ~25 mA, the slope efficiency is .04 W/A, which allows us to reach about 2 mW with only 80 mA driving current. Fig. 1b shows the output power versus bias voltage, we can observe that the device has a static extinction ratio in the range of 20 to 35 dB. The S21 curve of the device[8] (W1 connector)

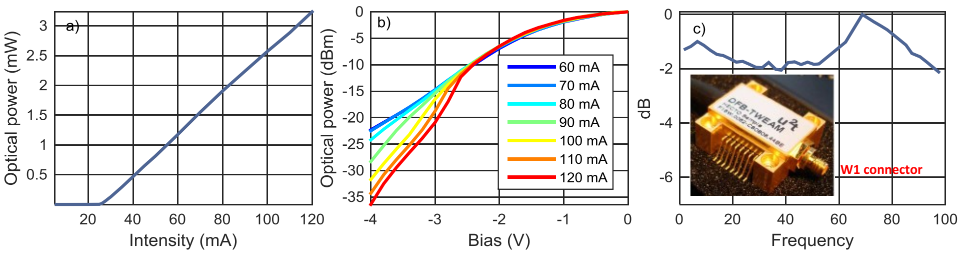

Fig. 1: a) P(I) characteristics b) P(V) characteristics c) S21 characteristics as measured in[8]

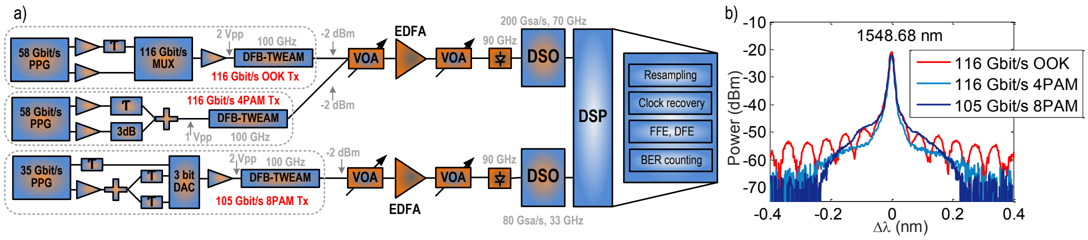

Fig. 2: a) Experimental setup. (PPG: pulse-pattern generator, Mux: Multiplexer, DAC: digital to analog converter T: Delay line, EDFA: erbium doped fiber amplifier, PD: Photodiode, DSO: digital storage oscilloscope, FFE: Feed forward equalizer, DFE: decision-feedback equalizer). b) Optical spectrum of the modulated signals (@ 0.01 nm resolution bandwidth)

depicted in Fig. 1c clearly shows beyond 100 GHz 3 dB bandwidth, the highest reported bandwidth to the best of our knowledge, with less than 2 dB ripple in the pass band of the EML which indicates high phase linearity. These figures of merits[8] are orders of magnitude better than state-of-art EMLs for optical interconnect.

Setup

Figure 2 shows a) transmitter setup for 116 Gbaud OOK, 58 Gbaud 4PAM and 35 Gbaud 8PAM with receiver setup including DSP and b) optical spectrum of the modulated signals. In the OOK setup, two PRBS15 signals at 58 Gbit/s are first decorrelated and then multiplexed into a single 116 Gbit/s. A 110 GHz traveling-wave limiting amplifier is used to drive EML. In the 4PAM setup, two PRBS15 are first decorrelated and then passively combined into a 4PAM signal, which is then used to directly drive the EML. In the 8PAM setup three PRBS15 sequences at 35 Gbit/s are first decorrelated and then combined in 3 bit DAC. A 65 GHz linear amplifier is used to drive EML. In all cases, the measured optical power out of the transmitter is -2 dBm. The receiver is composed of an erbium doped fiber amplifier (EDFA), variable optical attenuators (VOA), a high bandwidth photodiode (PD) and a 200 Gsa/s, 70 GHz bandwidth Tektronix digital sampling oscilloscope (DSO) (DPO77002SX) for OOK and 4PAM setups and 80 GSa/s, 33 GHz DSO for 8PAM setup. An automatic gain-controlled EDFA with fixed output power is employed as a pre-amplifier due to the low PD responsivity and the lack of transimpedance amplifier. The sampled signal is then processed offline using DSP. The clock recovery and resampling is performed on the received waveform to ensure 2 samples per symbol. The signal is then downsampled to 1 sample per symbol for symbol-spaced feed forward equalizer (FFE) with different number of taps to overcome inter symbol interference (ISI) or symbol-spaced decision-feedback equalizer (DFE) with different configuration of feed-forward taps (FFT) and feedback taps (FBT) to overcome ISI in presence of noise. The bandwidth limitation is due to limited effective 3 dB bandwidth on the transmitter side components used to generate the signals while as well limited DSO bandwidth in OOK and 8PAM setups.

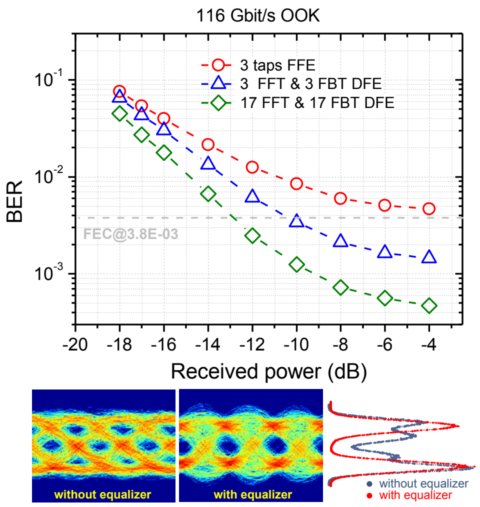

Fig. 3: (top) BER curves for 116 Gbit/s OOK. (bottom) Received eye diagram without and with equalizer and histograms for OOK at -2 dB input power

Results and Discussion

Obtained results provides the quantitative and qualitative evaluation of performance of the optical transmitter for its capabilities to enable 3rd generation 400G for optical interconnect applications. Figure 3 shows bit error rate (BER) curves for 116 Gbit/s OOK (on top) and the qualitative measure in terms of eye diagram and the histogram distribution of the received signal (on bottom). BER curves are obtained using different configurations of equalizers. One can observe that use of 3 FFT and 3 FBT DFE allows achieving below 7% FEC limit performance, which was further improved with larger taps number. The bottom section shows the received eye diagram and histogram with and without DSP for 116 Gbit/s OOK signal. We can see that the signal is limited by both ISI and noise. The histogram without equalizer shows level degeneration owing to the ISI which we

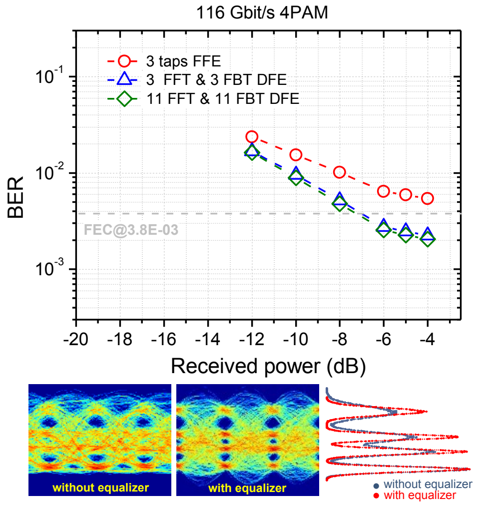

Fig. 4: (top) BER curves for 116 Gbit/s 4PAM. (bottom) Received eye diagram without and with equalizer and histograms for 4PAM at -2 dB input power

also observed in the electrical signal.

Figure 4 shows the BER curve (on top), eye diagram and histogram (on bottom) before and after equalizer for 116 Gbit/s 4PAM. We can see large degradation on the 4PAM signal owing to both higher sensitivity requirements and poor electrical performance at the transmitter. After FFE we can observe the passive combining ratio was suboptimal in the most significant bit, which explains the worse performance. We tried to use EML to compensate this effect by driving it at higher reverse bias voltage. We are able to improve the performance, however this causes compression on the upper levels and thus a trade-off was found. By adding 3 FFT and 3 FBT DFE, a BER below FEC limit was achieved.

Figure 5 shows BER curves for 105 Gbit/s 8PAM (on top) and eye diagram and the histogram distribution of the received signal (on bottom). Sensitivity for 8PAM is lower than 4PAM thanks to 3 bit DACs performance

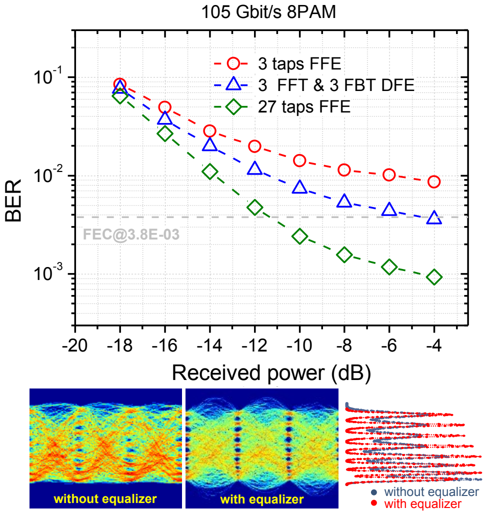

Fig. 5: (top) BER curves for 105 Gbit/s 8PAM. (bottom) Received eye diagram without and with equalizer and histograms for 8PAM at -2 dB input power

resulting in a lower implementation penalty. However still some compression is observed.

Therefore if we ensure sufficient bandwidth in electrical domain, the optical transmitter has the potential of transmitting >100 Gbaud signals with relatively low DSP requirements.

Conclusions

We report on performance of an EML with higher than 100 GHz bandwidth for optical interconnect applications. We experimentally validate its potential capabilities for high baudrate advance modulation formats by transmitting 116 Gbit/s OOK, 4PAM and 105 Gbit/s 8PAM signals. Furthermore, this is the first time that 116 Gbit/s OOK is achieved on a single EML based optical transmitter. Provided sufficient bandwidth and linearity on the electrical domain, this optical transmitter can be used to achieve advance modulation formats at higher than 100 Gbaud.

Acknowledgments

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