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100 GHz Externally Modulated Laser for Optical Interconnects

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Abstract—We report on a 116 Gbps on-off keying (OOK), 4 pulse amplitude modulation (PAM) and 105 Gbps 8PAM optical transmitter using an InP-based integrated and packaged externally modulated laser for high speed optical interconnects with up to 30 dB static extinction ratio and over 100 GHz 3 dB bandwidth with 2 dB ripple. In addition, we study the trade-off between power penalty and equalizer length to foresee transmission distances with standard single mode fiber.

Index Terms—distributed feedback laser (DFB), direct detection, electroabsorption modulator, optical interconnects.

I. INTRODUCTION

The third generation 400 Gbps client-side links are demanding a solution as the cloud services together with the huge size datasets are driving demand for bandwidth in datacenters [1],[2]. Potential solutions are under discussion within the IEEE P802.3bs 400 Gigabit Ethernet (GbE) Task Force [3]. One attractive solution is based on eight optical lanes (i.e., 8×50 Gbps). [4] thanks to compatibility with existing building blocks for 100 GbE (drivers, lasers, and photodetectors with transimpedance amplifiers). However, large lane count increases complexity and power consumption resulting in higher costs [1]. More scalable and cost efficient approach is to reduce number of lanes and increase the bandwidth for a single lane. Four optical lanes at 100 Gbps net rate (i.e., 4×100 Gbps/λ [5]) are a promising solution in order to reduce complexity, power consumption and costs.

II. EXTERNALLY MODULATED LASER

A. Previous Experimental Demonstrations

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 u’t Photonics [22],[23]. In [23], the performance of already packaged DFB-TWEAM transmitter module for 100 Gbps data rate is evaluated experimentally using 100 meters long standard single mode fiber (SSMF) and 10 km optical link with dispersion management. In [21] successful field trial is demonstrated with transmission of 112 Gbps OOK signals using a purely electrical time division multiplexing-based system without DSP. A bit error rate (BER) performance below the forward error correction (FEC) threshold of 2×10^{-3} is achieved after transmission over 42 km field installed SSMF with dispersion management between Kista and Råsunda in Sweden. It is the first demonstration of a complete 112 Gbps ETDM system based on monolithically integrated transmitter [23] and receiver modules.

B. Device Structure and Characterization

The TWEAM is based on the 12 strain-compensated InGaAsP quantum wells/barriers (QWs) of around 9 nm thickness each. The total active length of modulator is 180 µm. The gain section of the DFB is based on 7 QWs 7 nm thick grown by metal vapour phase epitaxy coupled with butt-joint technique. The laser is 440 µm long with a grating designed to have most of the output power towards the modulator. Components are formed in standard ridge waveguide structures [22]. Figure 1 shows the power versus current for unbiased modulator, power versus bias voltage and the frequency response taken at 22°C [24]. As we can see from Fig. 1a, the threshold current is ~25 mA, and 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 static extinction ratio versus bias voltage. We can observe that the device has a static extinction ratio in the range of 20 to 35 dB. The dynamic extinction ratio during modulation is related to modulator bias voltage and swing of driving voltage. The S21 curve of the device [22] (W1 connector) 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 [22] which indicates high phase linearity. These figures of merits [22] are order of magnitude better than state-of-art EMLs for optical interconnects.

III. EXPERIMENTAL SETUP

Figure 2 shows the transmitter setup for 116 Gbps OOK, 4PAM and 105 Gbps 8PAM with receiver setup including DSP (see Fig. 2a) and output optical spectrum of modulated signals (see Fig. 2b). In the OOK setup, two pseudo-random bit sequences with a word length of 2^{15}-1 (PRBS15) at 58 Gbps are first decorrelated and then multiplexed into a single 116 Gbps sequence. A 110 GHz traveling-wave limiting amplifier (TWA110 [25]) is used to drive the 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 Gbps are first decorrelated and then combined in a 3 bit DAC with 19 GHz analogue bandwidth. A 65 GHz linear amplifier is used to drive the EML. During measurements the bias voltage was kept at minus 2 volts and driving voltage was 2 Vpp for OOK, 8PAM and 1 Vpp for 4PAM. The average output power was kept at minus 2 dBm in all cases. The receiver is composed of an Erbium doped fiber amplifier (EDFA), variable optical attenuator (VOA), a high bandwidth photodiode (PD) from u’t with a responsivity of 0.5 A/W, and a 200 GSa/s, 70 GHz bandwidth Tektronix digital sampling oscilloscope (DSO) (DPO77002SX) for OOK as well as 4PAM setups, while 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. The signal is then downsampled to 1 sample per symbol for static/adaptive feed forward equalizer (FFE) with different number of taps to overcome inter symbol interference (ISI) or symbol-spaced adaptive decision-feedback equalizer (DFE) with different configuration of feed-forward taps (FFT) and feedback taps (FBT) to overcome ISI in presence of noise. The initial weights of the equalizer were obtained using training data with the normalized least-mean-square (NLMS) algorithm before applying other data. A total number of 1.2 million bits are used for BER counting. The bandwidth limitation is due to limited effective 3 dB bandwidth on the transmitter side components used to generate electrical signals, while additional filtering occurs due to the limited DSO bandwidth, affecting the performance of OOK and 8PAM setups.

IV. RESULTS AND DISCUSSIONS

Obtained results provide the quantitative and qualitative performance evaluation of the optical transmitter for its capabilities to enable the third generation 400 Gbps client-side links for optical interconnects. Figure 3 shows BER curves for 116 Gbps OOK (see Fig. 3a) and the qualitative measure in
We report on the performance of an EML with higher than 100 GHz bandwidth for optical interconnects. We experimentally validate its potential for fast optical interconnects by transmitting 116 Gbps OOK, 4PAM and 105 Gbps 8PAM signals. Furthermore, this is the first time [20] that 116 Gbps OOK is achieved on a single EML based

The EML to compensate this effect by driving it at high reverse bias voltage (-2 volts). 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&3-FBT DFE, a BER below FEC limit was achieved. We did not observe significant improvement by increasing the length of equalizer.

Figure 5 shows BER curves for 105 Gbps 8PAM (see Fig. 5a) and eye diagram and the histogram distribution of the received signal (see Fig. 5b). Similarly to previous cases BER curves are obtained using same configuration as before. Sensitivity for 8PAM is lower than 4PAM, but thanks to the performance of the 3 bit DAC, the implementation penalty is lower. However, still some compression is observed. One can observe that the performance of 3-FFT&3-FBT DFE is below the 7% FEC limit. Still performance can be significantly improved (reduction in power penalty is 4 dB with 27-tap static filter and 5 dB with 27-FFT&3-FBT DFE) with increased length of equalizer since the main bandwidth limitation is the 19 GHz bandwidth of the DAC. Therefore, by ensuring sufficient bandwidth in the electrical domain, the optical transmitter has the potential of transmitting >100 Gbaud signals with low DSP requirements.

Operational wavelength of the EML is around 1548 nm in these measurements. To complement the experiments we study chromatic dispersion tolerance for different modulation formats using Monte Carlo simulations. In simulation we assumed that all modulation formats are operated at 116 Gbps for a fair comparison. In simulations we focus on tolerance to chromatic dispersion (16ps/nm/km). Only bandwidth limitation is PD with responsivity of 0.5 A/W and 80 GHz bandwidth. Received power penalty as function of transmitted distance is shown in Fig. 6. We obtain curves for 3-tap and 6-tap static filter, 3-FFT and 6-FFT adaptive FFE, and 3-FFT&3-FBT and 6-FFT&3-FBT DFE. For 1 dB power penalty, the 116 Gbps OOK format can be transmitted up to 700 meters using 3-FFT&3-FBT DFE. The distance for 116 Gbps 4PAM can be increased about three times compared to OOK for same penalty and equalizer parameters. In case of 116 Gbps 8PAM, the dispersion penalty will be below 1 dB at 3 km distance using only a 3-tap static filter.

We point out that the microwave design of the transmitter can be applied to a semiconductor material with larger bandgap in order to achieve modulation at another operation wavelength [23]. Then transmission distances over SSMF can be significantly improved.

V. CONCLUSIONS

We report on the performance of an EML with higher than 100 GHz bandwidth for optical interconnects. We experimentally validate its potential for fast optical interconnects by transmitting 116 Gbps OOK, 4PAM and 105 Gbps 8PAM signals. Furthermore, this is the first time [20] that 116 Gbps OOK is achieved on a single EML based
optical transmitter with low complexity DSP. We study the trade-off between power penalty and equalizer length using Monte Carlo simulations. According to simulation results, a transmission of 3 km standard single mode fiber with less than 1 dB dispersion penalty using only 3-tap static filter for 116 Gbps 8PAM seems to be possible. We conclude that, provided sufficient bandwidth and linearity on the electrical domain, this optical transmitter can be used for advanced modulation formats at higher than 100 Gbaud.

REFERENCES


Oskars Ozolins (M’09) received M.Sc. degree in Telecommunications from Riga Technical University, Riga, Latvia, in 2009 and the Dr.ing (PhD) degree in Optical Communications from Riga Technical University, in 2013. Since 2014 he has been working at Acroo Swedish ICT AB where currently he is research scientist under Vetenskapsrådet project PHASE. He has recently been visiting researcher in DTU Fotonik, Technical University of Denmark, POTION Laboratory (CNRS UMR 6082), ENSSAT, University of Rennes 1, and Gent University. His research interests are in the areas of fiber-optic communications, photonic-wireless systems, optical signal processing, and high speed short-range transmission. He is the author or co-author of around 60 international publications, conference contributions, and book chapters. He holds one patent. He has regularly served as a designated reviewer for OSA Journals: Chinese Optics Letters, Applied Optics, Optics Express, and Photonics Research.

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