Beyond 200 Gbps per Lane Intensity Modulation Direct Detection (IM/DD) Transmissions for Optical Interconnects: Challenges and Recent Developments

Xiaodan Pang[1,4], Oskars Ozolins[2,1], Lu Zhang[1,3], Aleksejs Udalcovs[2], Rui Lin[1], Richard Schatz[1], Urban Westergren[1], Shilin Xiao[3], Weisheng Hu[3], Gunnar Jacobsen[2], Sergei Popov[1], and Jiajia Chen[1]
[1]*KTH Royal Institute of Technology, Kista, Sweden*
[2]*NETLAB, RISE Research Institute of Sweden, Kista, Sweden*
[3]*State Key Laboratory of Advanced Optical Communication System and Networks, Shanghai Jiao Tong University, Shanghai, China*
[4]*Infinera, Stockholm, Sweden*
xiaodan@kth.se

Abstract: All parts of an IM/DD system are being stretched to the limit as the single lane data rate approaches 200 Gbps and beyond. We report the recent developments on the key enablers conquering this target.

OCIS codes: (060.4510) Optical communications, (200.4650) Optical interconnects

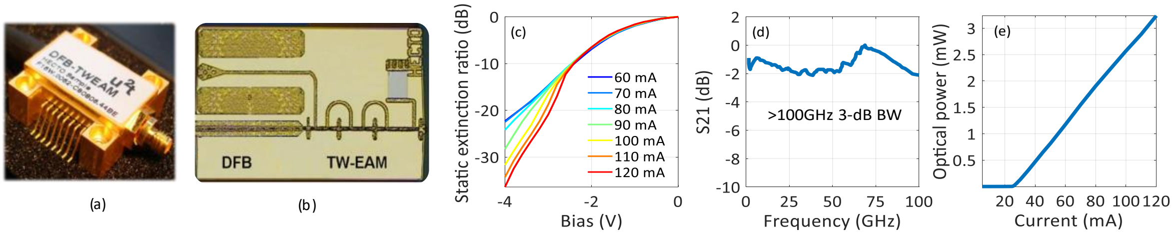
1. Introduction

Continuously growing amount of data exchange in and across data centers drives the continuous development in high-speed interconnect technologies. To date, the intensity modulation direct detection (IM/DD) solutions still dominate the market of short reach optical interconnects, before its coherent counterpart closes the gap of cost, complexity and power consumption. Efforts are put in all different aspects, including components, signaling formats and digital signal processing (DSP) techniques, to meet the requirements of high-speed, low-cost and small footprint [1]. Broadband electronic and optoelectronic components are being designed and demonstrated to enable over 100 GBd signal generation and modulation [2-5]. Advanced modulation formats including pulse amplitude modulation (PAM) and discrete multi-tone (DMT) of data rate over 200 Gbps are demonstrated [3-7]. Powerful and sophisticated DSP algorithms and coding methods, such as feedforward and feedback adaptive equalizers, Volterra-based filters, and/or maximum likelihood sequence estimator (MLSE) based soft decoders are developed to recover the signal from distortions, mainly caused by limited channel bandwidth and nonlinearities during the optical to electrical (O/E) and E/O conversions [6,7]. To be able to justify the advantages of the IM/DD over the coherent solutions, the trade-off between complexity in both hardware resources and the DSP should be balanced.

In this work we review the recent developments in approaching and conquering the 200 Gbps single lane data rate and beyond. And we discuss the remaining challenges, with a focus on the single digital to analog converter (DAC), single laser and modulator, and single photodetector (PD) solution.

2. Optoelectronic components

One key enabler to achieve 200 Gbps are the optoelectronic components for O/E and E/O conversion, for which the EU FP6 HECTO project is acknowledged [8]. A monolithically integrated distribution-feedback laser and a traveling-wave electro-absorption modulator (DFB-TWEAM) module is designed by KTH, fabricated by KTH and former Syntune, and packaged by former u^{2}t Photonics [9]. Figures 1(a)-(b) show the packaged DFB-TWEAM module and a micrograph of the monolithic chip structure. The static extinction ratio of the module, the small signal transfer response of the chip, and the PI curve are presented in Figs. 1 (c)-(e), respectively. The DFB-TWEAM operates at C-band and there is a tradeoff between extinction ratio and output power due to level of absorption, which should always be balanced and optimized case by case. The 3-dB modulation bandwidth of the EAM is beyond 100 GHz, and the modulation linearity supporting multilevel modulation formats was verified [10,11].



(a) (b)

Fig.1. DFB-TWEAM: (a) packaged module; (b) microphotograph of the chip; (c) static extinction ratio vs. bias voltage; (d) small-signal transfer characteristics S21; and (e) output power of the unbiased modulator vs. laser current.

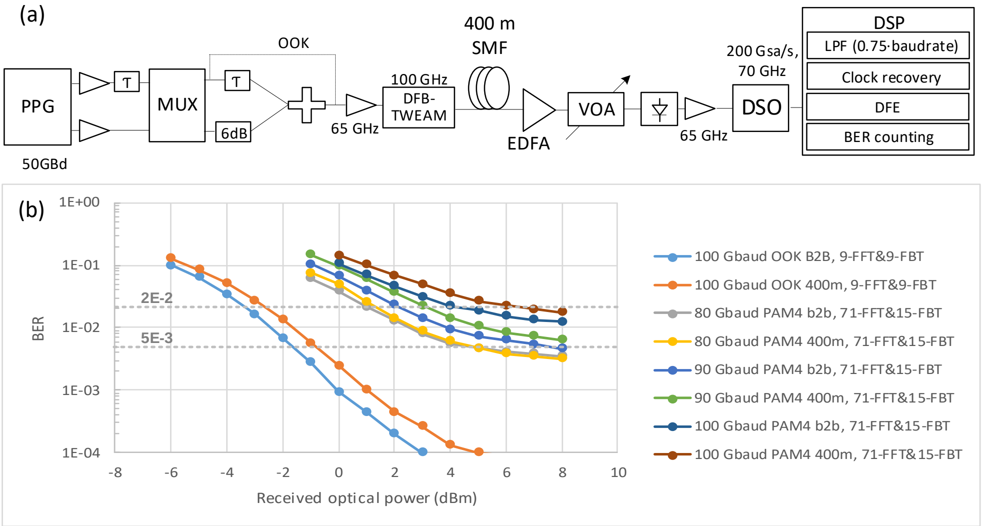


Fig.2. 100GBd OOK and PAM-4: (a) setup and (b) BER performance for B2B and 400-m transmission

Besides the DFB-TWEAM, other broadband components of 3-dB bandwidth over 100 GHz are also prototyped during the HECTO project, including limiting driver amplifiers, 2:1 multiplexers and photodetectors [12]. Together with the DFB-TWEAM, these broadband components can relax the channel bandwidth limitations to a great extent, which potentially release the DSP complexity by offering better signal quality.

3. Modulation formats and DSP

The bandwidth and noise performance of the components across the end-to-end system set the fundamental channel limit, and the use of advanced modulation formats and effective DSP algorithms can facilitate the system to approach the channel limit. In our experimental works, to reach 200 Gbps and beyond with the limited analog bandwidth of signal generator, such as the pulse pattern generator (PPG) or arbitrary waveform generator (AWG), advanced modulation formats, e.g. PAM-4 and DMT are used [13,14]. Figure 2(a) shows the experimental setup in generating and transmitting up to 100 GBd on-off keying (OOK) and PAM-4 signals. In this setup the bottleneck for the signal quality was the passive ‘attenuate and combine’ way of generating the PAM-4 signal, which could not assure an optimal linearity. On top of that the cascaded filtering effect from the power combiner, the driver amplifier and the pre-amplifier further distorts the signal, which is not Nyquist pulse shaped. Consequently, decision feedback equalizer (DFE) with many taps are required at the receiver to compensate the impairments. Figure 2(b) shows the measured bit-error-rate (BER) versus the received optical power at the PD for OOK and PAM-4 at different baud rates. It is clearly seen that by upgrading OOK to PAM-4 at the same baud rate, there is a significant drop in receiver sensitivity with considerably increased DFE complexity.

Figure 3 shows our experimental setup and results of the DMT transmission. A 92 GSa/s AWG was used to generate the bit and power loaded DMT signal of over 200 Gbps line rate. After removing 20% forward error correction (FEC) code overhead, the achieved net data rates at different distances are shown in Fig.3(b). The main limit is the 32 GHz analog bandwidth of the AWG output. In addition, the DMT signaling suffers from a high peak to average power ratio (PAPR), and thus gets distorted during the modulation at the EAM to ensure a high output power. Consequently, at the receiver, a Volterra-based time domain nonlinear equalizer (TD-NE) compensating the nonlinear distortions is necessary. By comparing the BER results shown in Fig.3(c) with Fig.2(b), one can see that the DMT signal has the potential to reach a longer distance comparing to PAM-4 at the C-band, at the cost of higher DAC resolution and complex DSP.

4. Discussions and conclusions

The high complexity in the DSP to compensate for the signal distortions in both PAM-4 and DMT can only be relaxed by a better signal quality. There are potential ways for further improvements on top of our current implementations with the broadband HECTO components. Firstly, the bandwidth and linearity bottlenecks in the signal generation can be improved by using a DAC of higher analog bandwidth and a better effective number of bits (ENOB). Secondly, higher integration between the electronics and the optics with joint optimization could offer better signal integrity. As a step forward, a demonstration of up to 200 GBd OOK transmission was successfully achieved with the HECTO components [15,16], by improving on the modulated signal quality.

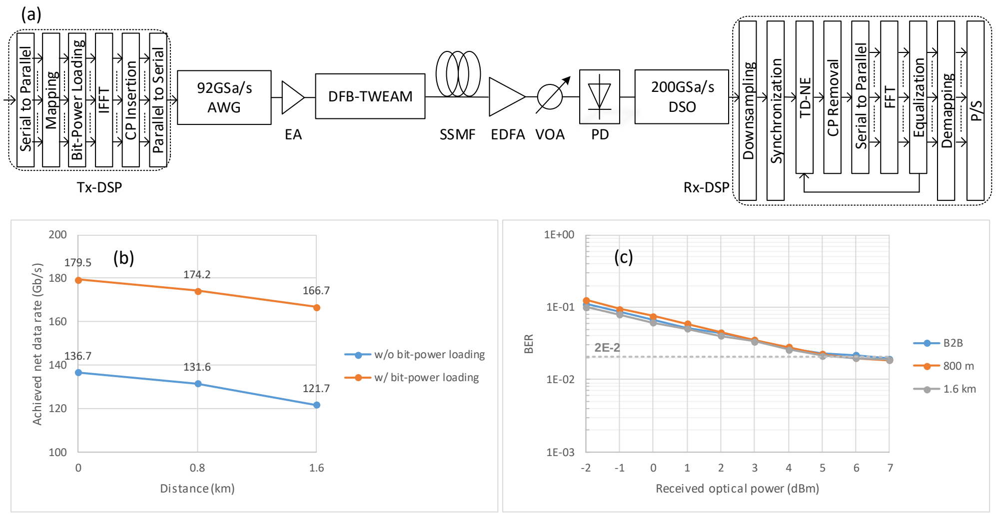


Fig.3. DMT: (a) setup; (b) achieved net data rate vs. distance and (c) BER performance for B2B and up to 1.6-km transmission

We review and discussed the key enabling technologies to realize single lane IM/DD transmission data rate of 200 Gbps and beyond. The fundamental limits for the achievable data rate in such system lie within the electrical and optoelectronic components, particularly the bandwidth and noise performance. Such limits can be approached by employing effective modulation formats with DSP algorithms. Future effort in reducing the complexity and cost of DACs/ADCs with high ENOB and broadband and the DSP implementations will be the key challenges to address. On the other hand, fair and detailed comparisons in terms of the performance and complexity with its coherent counterpart for various application scenarios become a timely relevant necessity.

5. Acknowledgement

This work is supported in part by EU H2020-MCSA-IF project 752826 NEWMAN, SJTU State Key Laboratory of Advanced Optical Communication System and Networks Open Project 2018GZKF03001, Swedish Research Council (VR) project 2016-04510 "PHASE", 2016-04489 "Go-iData", the Swedish ICT–TNG project SCENE, Swedish Foundation for Strategic Research (SSF), Göran Gustafsson Foundation and Vinnova funded Celtic Plus sub-project C2015/3-5 SENDATE-FICUS and SENDATE-EXTEND. The Knut and Alice Wallenberg Foundation is acknowledged for equipment funding and Keysight and Tektronix for equipment loan.

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