Demonstration of 214Gbps per lane IM/DD PAM-4 transmission using O-band 35GHz-class EML with advanced MLSE and KP4-FEC

Weiyu Wang[1], Zhilei Huang[2], Biwei Pan[3], Huanlu Li[2], Guanpeng Li[3], Jian Tang[1], Yuchun Lu[2*]

[1] Analog Design Dept, HiSilicon, Beijing, 100095 China
[2] Network Technology Laboratory, Huawei Technologies Co. Ltd., Beijing, 100095 China
3 Opto-Electronics Dept, HiSilicon, Wuhan, China
**yuchun.lu@huawei.com*

Abstract: A single-wavelength single-polarization 35GHz-class (112Gbps-class) commercial EML-based IM/DD 214Gbps PAM4 signal transmission is experimentally demonstrated. By using advanced MLSE with low complexity and power consumption, the BER is below standard KP4-FEC requirement of 2×10^{-4}.

1. Introduction

Propelled by bandwidth-hungry Internet of Things (IoT), cloud-centric network services, continuously growing amount of data exchange intra- and inter- data center drives the development of high speed short-reach optical interconnect technologies at 100Gbps and beyond. Before coherent counterpart closes the gap of cost, complexity and power consumption, the intensity modulation/direct detection (IM/DD) scheme will still be the most competitive solution for short reach optical interconnections.

Several 200Gbps per lambda IM/DD researches have been reported recently. Ultra broadband transmitters have been developing dramatically. Monolithically integrated distribution-feedback laser and traveling-wave electro-absorption modulator (DFB-TWEAM) with 100GHz bandwidth [1], lumped-electrode EADFB laser with a modulation bandwidth of 59 GHz [2] that are verified to support 200Gbps transmission. Multilevel modulation formats and advanced digital signal processing (DSP) algorithms allow the system to approach the bandwidth and signal to noise ratio (SNR) limit. 200Gbps DMT transmission was demonstrated based on time domain nonlinear equalizer (TD-NE) [3] and cylindrical vector beam (CVB) multiplexing over few-mode fibre [4]. 106GBaud PAM8 transmission was demonstrated with BER of 3.8×10^{-3} over 1-km non-zero dispersion-shifted fibre transmission based on pre equalization and probabilistic shaping [5]. 255Gbps PAM-8 transmission by applying nonlinear maximum likelihood sequence (NL MLSE) with third-order Volterra filter was experimentally verified [6]. To fully utilize the advantages of the IM/DD configuration, the advanced algorithm with low power consumption in both optical component and DSP architecture are highly concerned.

In this paper, we propose an advanced MLSE algorithm of low complexity and power consumption with register-transfer-level-complied (RTL-complied) DSP offline model. By using O-band 35GHz-class commercial electro-absorption modulated laser (EML) and our advanced MLSE DSP, we experimentally demonstrate a PAM4 transmission with line rate of 214Gbps with standard KP4-FEC for intra-data center interconnections. Sensitivity of -3dBm at 2×10^{-4} (KP4-FEC) is achieved for the first time. The link budget reaches as large as 5.4dB in consideration of 2.4dBm launch power, which means that 10km transmission of 214Gbps is achievable at O-Band.

2. Advanced MLSE Architecture

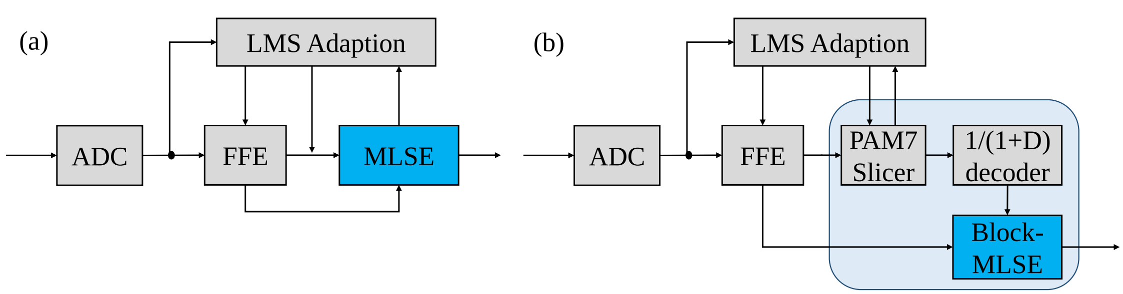

Fig. 1. The schematic diagram of the advanced DSP.

Two advanced receiver MLSE DSP schemes are shown in Fig. 1. In each schemes, the output of the ADC provides an input signal to the following equalizer. The ADC sliced data is first linearly equalized by the FFE to get a (1+D) channel. The FFE tap number can be adjusted according to the length of Inter-Symbol Interference (ISI) channel. The coefficients of all the FFE taps are adapted by the LMS algorithm that could guarantee the optimal performance. The receiver DSP with FFE and MLSE is shown in Fig. 1(a) [7]. MLSE tests all possible data sequences drawn from the alphabet and picks the one with the maximum probability as the output, which is necessary when received signal has large amount of ISI. In comparison, the traditional MLSE is more complicated in comparison with block-MLSE, shown in Fig. 1(b). A PAM-4 signal going through (1+D) channel will become a PAM-7 signal, and then be sliced directly. The sliced PAM-7 signal will then be decoded to PAM-4 signals with a 1/(1+D) decoder. The 1/(1+D) decoder can detect the end of burst error (EoBE) due to error propagation. The block-MLSE engine can be activated when error occurs. As a result, the complexity and power consumption can be reduced drastically, with performance reserved. The 1/(1+D) decoder has the identical error propagation characteristics with decision feedback equalization (DFE), DFE-based (1+D) MLSE that can also be regarded as a potential effective DSP scheme[8].

3. Experiment Setup

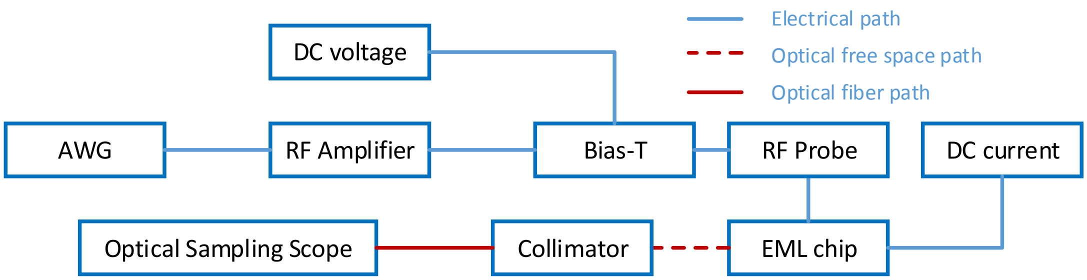

Fig. 2. Experimental setup of single wavelength PAM-4 signal transmission.

The experimental setup of the 214Gbps PAM-4 signal transmission with advanced DSP flow is illustratively pictured in Fig. 2. The 120GSa/s arbitrary waveform generator (AWG) with bandwidth of 45GHz is used to generate PRBS15 PAM-4 electrical signal. The output signal is pre-processed with a raised cosine filter for anti-aliasing and pre-emphasis for compensating the insertion loss of the AWG. The output of the AWG is connected to an RF amplifier with the bandwidth of 66GHz. After being amplified, the output signal is combined with a DC signal with the help of a 65-GHz-bandwidth bias-T of and applied to the EML by an RF probe with 67GHz bandwidth. The output light signal of the EML is then coupled to fibre by a collimator with maximum coupling efficiency of about 50%. Finally, the optical signal is received by an optical sampling oscilloscope to reconstruct the modulation signal. Another channel of the AWG with output of quarter frequency clock signal is also connected to the optical sampling oscilloscope to provide the synchronization signal. During the measurement, the variation of the received optical power (ROP) is achieved by adjusting the distance between the fibre collimator and the EML.

The performance of the commercial 35GHz-class EML for 112Gbps applications used in this work is shown in Fig. 3. The center wavelength of the EML is 1310nm. The end-to-end S-parameter of the whole measurement system is shown in Fig. 3(a), which indicates that the S-parameter drops significantly after 40 GHz. The eye-pattern of the 112Gbps PAM-4 signal is shown in Fig. 3(b).

4. Results

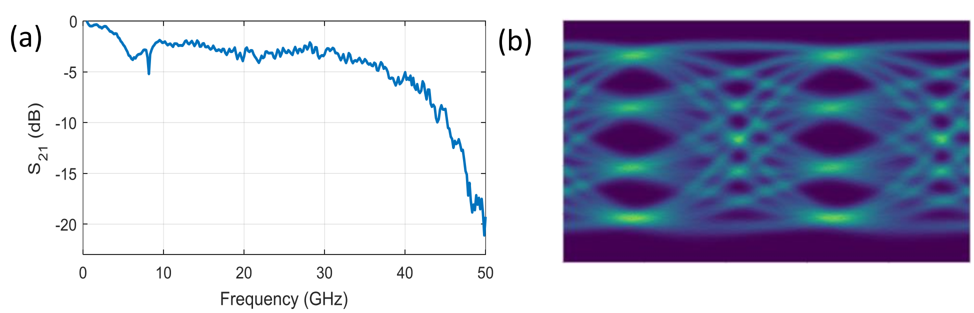

Fig. 3. Measured (a) end-to-end S-parameter of the whole system (b) eye-pattern of the 112Gbps PAM-4 signal.

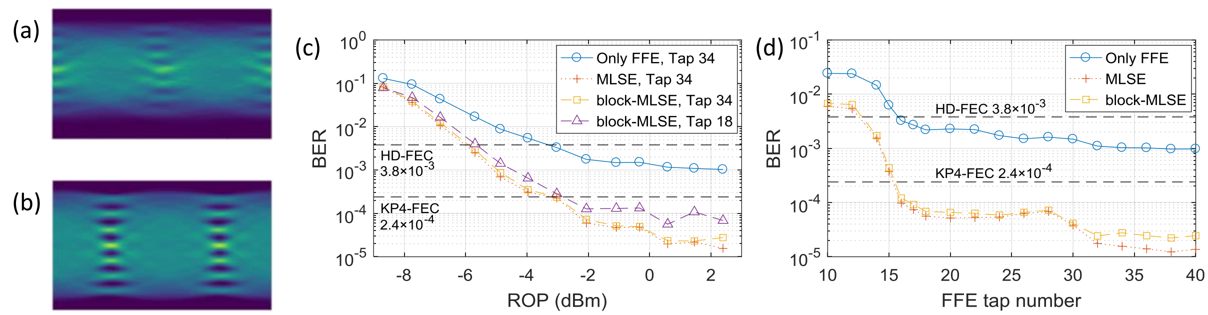

Fig. 4. Measured eye diagram of signals (a) before and (b) after FFE . BER performances versus (c) ROP and (d) FFE tap number.

The eye-diagram obtained by the optical sampling oscilloscope for the 214Gbps signal at the maximum ROP of 2.4dBm is shown in Fig. 4(a). The eye is not clear due to too much ISI introduced by the bandwidth and SNR limit. With 34-tap FFE adapted by the off-line program applied to the data, the PAM-7 eye-diagram of the equalized (1+D) data is shown in Fig. 4(b).

The BER curves versus ROP for 214Gbps per lane transmission based on different equalization are shown in Fig. 4(c). 34-tap FFE is used in this experiment, while the BER floor can only reach 1.0×10^{-3} without MLSE. By using MLSE or block-MLSE, the BER error floor is lower than 2.4×10^{-4}, which is the KP4-FEC limit, with ROP greater than -3dBm. The sensitivity at 3.8×10^{-3} (HD-FEC limit) is -5.7dBm. This indicates that larger than 200Gbps payload data excluding the FEC overhead can be transmitted without error through this channel. Besides, the penalty between the full-speed MLSE and the block-MLSE is negligible. Block-MLSE is a very promising DSP scheme to achieve low complexity and low power consumption while maintaining high performance simultaneously. The link budget is 5.4dB (8.2dB) in consideration of the launch power of 2.4dBm for KP4-FEC (HD-FEC) limit. As the optical coupling efficiency is only 50%, the link budget can be further improved in practical implementations. Therefore, at least 10 km transmission is achievable by applying EML and Block-MLSE, considering the ignorable dispersion effect in 1310nm. To the best of our knowledge, this is the longest reported transmission distance in 214Gbps PAM-4 EML-based system.

The BER curves versus FFE tap-number at maximum ROP is shown in Fig. 4(d). It shows that by using block-MLSE with only 16 tap FFE, the BER can also meet the requirement of the KP4-FEC limit of 2.4×10^{-4}, which will further reduce the power consumption.

5. Conclusion

In this work, we have demonstrated a 214Gbps PAM-4 signal transmission with 35GHz-class EML at O-band with a single-wavelength, single-polarization, and IM/DD configuration. By applying RTL-complied equalization of block-MLSE, receiver sensitivity of -3dBm at KP4-FEC limit is achieved for the first time. The obtained results denote that EMLs with advanced DSP can act as a promising 200Gbps per lambda low cost and low power consumption technology scheme for future DC interconnections. In our view, it will become a competitive solution for the next 800GE and 1.6TbE applications.

6. References

[1] O. Ozolins et al., "100 GHz externally modulated laser for optical interconnects," J. Lightw. Technol. 35 (6), 1174-1179 (2017).

[2] S. Kanazawa et al., "Transmission of 214-Gbit/s 4-PAM signal using an ultra-broadband lumped-electrode EADFB laser module," in Proc. OFC 2016, Th5B.3.

[3] L. Zhang et al., "Nonlinearity-aware 200 Gbit/s DMT transmission for C-band short-reach optical interconnects with a single packaged electro-absorption modulated laser," Opt. Lett. 43(2), 182-185 (2018).

[4] Y. Sun et al., "Demonstration of low-cost EML based 240 Gbit/s DFT-spread DMT signal transmission over few-mode fiber with cylindrical vector beam multiplexing," IEEE Access, 7, 2169-3536(2019).

[5] J. Zhang et al., "Demonstration of 260-Gb/s single-lane EML-based PS-PAM-8 IM/DD for datacenter interconnects," in Proc. OFC 2019, W4I.4.

[6] A. Masuda et al., "255-Gbps PAM-8 transmission under 20-GHz bandwidth limitation using NL-MLSE based on volterra filter," in Proc. OFC 2019, W4I.6.

[7] W. Wang et al., "Advanced digital signal processing for reach extension and performance enhancement of 112 Gbps and beyond direct detected DML-based transmission," J. Lightw. Technol. 37(1), 163-169(2019).

[8] Y. C. Lu, et al. "Elimination of DFE error propagation and Post-FEC error floor", (Precoding 2.0) http://www.ieee802.org/3/ck/public/19_03/lu_3ck_01_0319. pdf.