100 GBAUD PAM4 LINK WITHOUT EDFA AND POST-EQUALIZATION FOR OPTICAL INTERCONNECTS

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Abstract

We achieve 300 Gbps line rate transmission with 100 Gbaud PAM8 over 400 meters of SSMF in C-band. We also demonstrate 100 Gbaud PAM4 400 meters link below the 7% HD-FEC limit of $5{\cdot}10^{-3}$ without optical amplification and post-equalization.

1 Introduction

Fast, reliable and secure exchange of information is a must for a modern society and requires access anywhere. Emerging technologies for Data Centre traffic, 5G mobile optical front-haul and back-haul systems, medical applications, traffic safety and society security are stretching the requirements for seamless connectivity. Technical and economic challenges arise to keep up the bandwidth density and scalability. Cost-efficient short reach optical interconnects for 400 GbE intra-datacentre links are critical. Attractive solutions are proposed based on four optical lanes [1] thanks to compatibility with 100GbE building blocks. Solutions for 400 GbE based on two optical lanes [2, 3, 5, 4, 6, 7] or even single lane [8] using high bandwidth components may be more attractive to overcome cost and energy crunch while reducing complexity of parallelism.
Optical interconnects operating at 100 Gbaud and beyond per lane are required to confront the growing bandwidth density and scalability Data Centres. Industrial solution for co-designed and co-integrated electronics and photonics is around the corner since required building blocks are available: high-performance integrated circuits capable of generating ultrahigh bandwidth PAM4 [8, 10] even without any equalization [11]; beyond high bandwidth modulators and photodetectors [4,7,12]; and scalable analogue to digital converter (ADC) frontend enabling reception [13]. Critical point is to avoid using erbium doped fibre amplifiers (EDFAs) and to reduce complexity of digital signal processing (e.g. removing post-equalization). For on-off keying with Mach-Zehnder modulators it is demonstrated at 140 Gbaud without amplification [9] still requiring adaptive post-equalization due to the severe modulator bandwidth limitation.
In this paper we experimentally evaluate 100 Gbaud 4-level pulse amplitude modulation (PAM4) and 8-level PAM (PAM8) link in C-band for short reach optical interconnects. We demonstrate 100 Gbaud PAM4 transmission over 400 meters long standard single mode fibre without optical amplification and without post-equalization below 7% overhead (OH) forward error correction (FEC) pre-FEC bit error rate (BER) limit at $5{\cdot}10^{-3}$. Achieved result shows significantly improved signal performance [5,14]. We also achieve 300 Gbps line rate with 100 Gbaud PAM8 after 400 meters below pre-FEC BER of $2.7{\cdot}10^{-2}$ with post-equalization which is compelling improvement compared to previous achievement [15].

2. Methodology

The experimental setup is shown in Fig 1. The 100 Gbaud PAM signal is generated offline using a 2^{15}-1 long pseudorandom binary sequence (PRBS). Then it is up-sampled

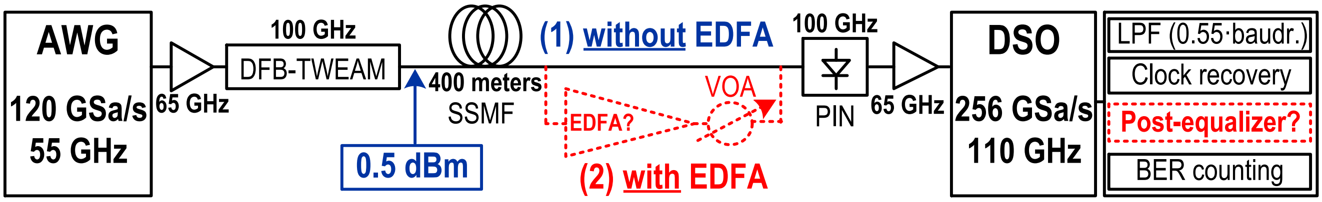

Fig. 1 experiment setup for 100 Gbaud PAM4/8 transmission with & without EDFA and post-equalization

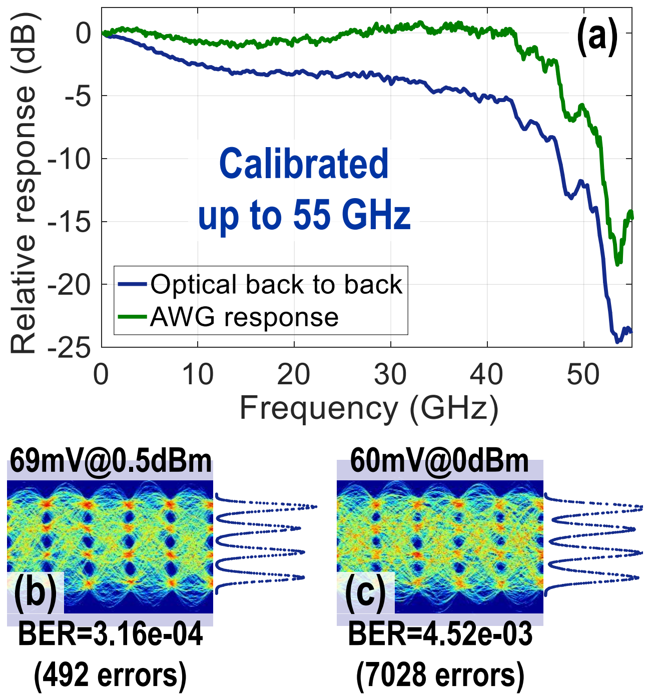

Fig. 2 (a) relative response for AWG and ob2b configuration, 100 Gbaud PAM4 eye diagram for ob2b (b) and after 400 meters (c) of SSMF

and filtered with a root-raised-cosine (RRC) filter having 0.15 roll-off factor. Frequency domain pre-equalization up to 55 GHz is used to compensate for the state-of-the-art bandwidth (BW) of 120 GSa/s arbitrary waveform generator (AWG). One can observe (see Fig 2 (a)) that optical back to back (ob2b) response is following close the one of the AWG. After pre-equalization 100 Gbaud PAM signal is loaded to AWG. Then it is amplified in a 65 GHz electrical amplifier with 11 dB gain. Similar is used after PIN photodetector.

A monolithically integrated distributed feedback laser-travelling wave electro-absorption modulator (DFB-TWEAM) is used to generate optical signals (3 dB BW >100 GHz [12]). We obtain 0.5 dBm output power when TWEAM is biased at minus 1.83 volts and DFB is driven with 120 mA current. We use different sample compared to previous experiments resulting in higher output power. Estimated extinction ratio for modulated signal is ~ 4.5 dB with power consumption of about 400 mW. Operational temperature of the externally modulated laser (EML) package is ~ 20 °C. Further improvements on EML will be required to reduce required driving swing to about 0.5-0.8Vpp while maintaining optical modulation performance (output power and extinction ratio etc.). EML technology can in principle be co-designed and co-integrated to enable the most efficient solution for challenge of scalability and bandwidth density in Data Centre connections.

We evaluate two link configurations (see Fig 1). In first configuration (without EDFA) we connect the EML output through standard single mode fibre (SSMF) directly to a PIN photodetector (3 dB BW >90 GHz, Responsivity=0.5 A/W). In second (with EDFA) we use pre-amplifier followed with a variable optical attenuator (VOA) to adjust the power before the PIN photodetector. The signal is captured with a 256 GSa/s 110 GHz digital storage oscilloscope (DSO). Then sampled signal is processed offline using digital signal processing (DSP) routine consisting of a low-pass filter (LPF), a maximum variance timing recovery, and an error counter. For PAM4 we use 1515520 bits and for PAM8 2273280 bits. We also look at the improvement provided by the post-equalization which is based on a symbol-spaced decision-feedback equalizer (DFE) with different configurations of feed-forward taps (FFT) and feedback taps (FBT).

3 Results

Several FEC codes are considered for result analysis. For PAM4 we use hard decision (HD)-FEC with 7% OH (pre-FEC BER limit at $5 \cdot 10^{-3}$) [16] and KP4 with 4% OH (pre-FEC BER limit at $2.2 \cdot 10^{-4}$) [17]. For PAM8 we use soft decision (SD)-FEC with 20 % OH (pre-FEC BER limit at $2.7 \cdot 10^{-2}$) [18] and SD-FEC with 27% OH (pre-FEC BER limit at $4 \cdot 10^{-2}$) [19]. We evaluate 100 Gbaud PAM4/8 signal transmission over 400 meters of SSMF with and without EDFA and post equalization.

On Fig 2 we show relative response for 120 GSa/s AWG and ob2b both measured up to 55GHz. We also show eye diagrams for 100 Gbaud PAM4 signal for ob2b and after 400 meters of SSMF. BER values shown as inset are below $5 \cdot 10^{-3}$ for the first configuration (without EDFA). We use LPF_{BW} of 0.55·Baudrate.

On Fig 3 we study first configuration (without EDFA). We show BER as function of LPF_{BW}/Baudrate for 100 Gbaud

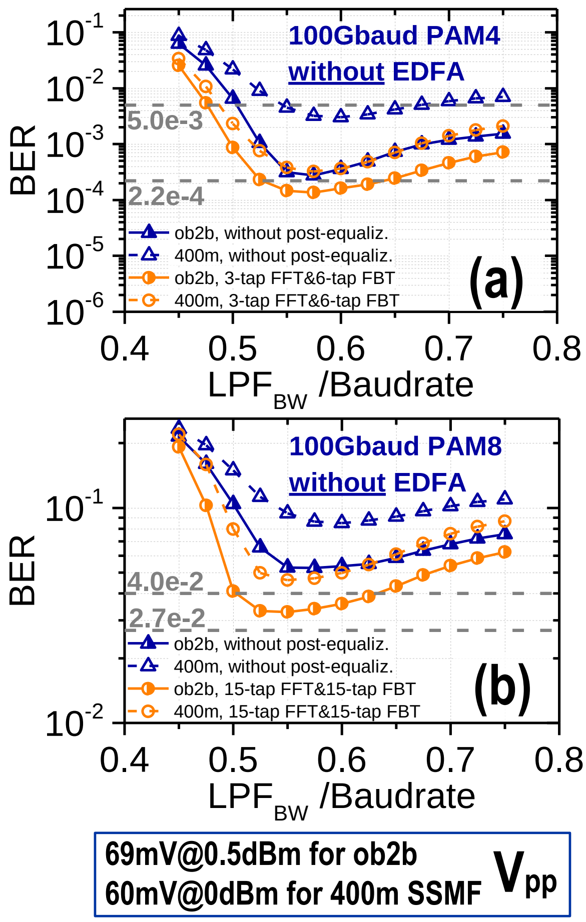

Fig. 3 BER versus LPF_{bw}/baudrate for PAM4 (a) and PAM8 (b) for first configuration (without EDFA), V_{pp} measured at DSO are shown as inset

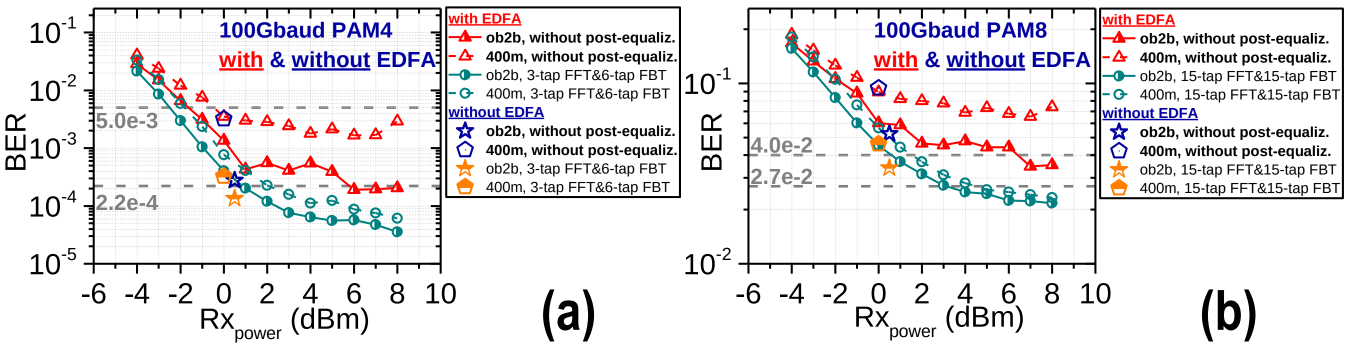

Fig. 4 BER versus Rx_{power} for PAM4 (a) and PAM8 (b) in both configurations

PAM4/8. We also show V_{pp} measured at DSO for ob2b and after 400 meters of SSMF as inset. For PAM4 both curves are below $5{\cdot}10^{-3}$ without post-equalization. Similar performance for ob2b and after 400 meters is obtained with 3-tap FFT & 6-tap FBT equalizer for later one and ob2b without post-equalization. For PAM8 we manage to obtain BER performance below $4{\cdot}10^{-2}$ only for ob2b with 15-tap FFT & 15-tap FBT equalizer. This shows that for PAM8 higher received optical power is required.

On Fig 4 we compare both configurations (without & with EDFA). We show BER as a function of received power (Rx_{power}). Both configurations result in similar performance without post-equalization (see **blue star** when 0.5 dBm for ob2b and **blue pentagon** when 0 dBm for 400 meters). For PAM4 use of EDFA allow to achieve KP4 pre-FEC BER limit of $2.2{\cdot}10^{-4}$ thanks to higher received power. We see that BER performance is also improved below $4{\cdot}10^{-2}$ without post-equalization for PAM8. We observe ~ 1 dB penalty and require ~ 4 dBm optical power at $2.7{\cdot}10^{-2}$ pre-FEC BER limit with 15-tap FFT & 15-tap FBT equalizer. We are considering pre-FEC BER of $2.7{\cdot}10^{-2}$ [18] for PAM8 with post-equalization. Performance margin improves by 3 dB when we consider pre-FEC BER of $4{\cdot}10^{-2}$ [19]. Post-equalization gives the most improvement for the signal after transmission after 400 meters. We observe that consistently through Fig 3 and 4.

Even though scaling modulation order gives higher capacity and using higher that four levels seems to be technically challenging due to intrinsic penalty for eye opening reduction [3]. One needs to consider the complexity of signal processing when moving to PAM8. Further improvements would be required both in generation and signal processing to enable higher-level modulation but at a cost of too high for optical interconnects.

4 Conclusion

Single lane 100 Gbaud PAM4 optical interconnects are around the corner and can be implemented without need of optical amplifier e.g. EDFA and with reduced signal processing by avoiding post-equalization. Solution may be cost- and power-efficient to enable next generation of Data Centre intra-connections.

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6 References

[1] Zhong, K., Mo, J., Grzybowskiet, R., al.: '400 Gbps PAM-4 Signal Transmission Using a Monolithic Laser Integrated Silicon Photonics Transmitter'. Proc. of OFC, San Diego, USA, March 2019, paper Tu2I.4.

[2] H. Mardoyan, M. A. Mestre, J. M. Estarán, et al.: '84-, 100-, and 107-GBd PAM-4 Intensity-Modulation Direct-Detection Transceiver for Datacenter Interconnects', Journal of Lightwave Technology, 2017, **35**, (6), pp 1253-1259, DOI: 10.1109/JLT.2016.2646327

[3] C. Yang, W. Li, S. Yu,: 'Single channel 224 Gbit/s (56-GBaud) PAM-16 transmission using linear digital pre-distortion', Electronics Letters, 2017, **53**, (21), pp 1420-1422, DOI:10.1049/el.2017.2436

[4] S. Lange, S. Wolf, J. Lutz, et al.: '100 GBd Intensity Modulation and Direct Detection with an InP-Based Monolithic DFB Laser Mach–Zehnder Modulator', Journal of Lightwave Technology, 2018, **36**, (1), pp 97-102, DOI: 10.1109/JLT.2017.2743211

[5] Ozolins, O., Pang, X., Udalcovs, A., et al.: '100 Gbaud 4PAM Link for High Speed Optical Interconnects'. Proc. of. ECOC, Gothenburg, Sweden, September 2017, pp 1-3.

[6] J. M. Estarán, H. Mardoyan, F. Jorge, et al.: '140/180/204-Gbaud OOK Transceiver for Inter- and Intra-Data Center Connectivity', Journal of Lightwave Technology, 2019, **37**, (1), pp 178-187, DOI:10.1109/JLT.2018.2876732

[7] B. Baeuerle, W. Heni, C. Hoessbacheret, al.: 'Reduced Equalization Needs of 100 GHz Bandwidth Plasmonic Modulators', Journal of Lightwave Technology, 2019, Early access DOI:10.1109/JLT.2019.2897480

[8] Chen, X., Chandrasekhar, S., Cho, J., et al.: "Single-Wavelength and Single-Photodiode Entropy-Loaded 554-Gb/s Transmission over 22-km SMF'. Proc. of OFC, San Diego, USA, March 2019, paper Th4B.5.

[9] Ozolins, O., Estarán, J. M., Udalcovs, A., et al.: '140 Gbaud On-Off Keying Links in C-Band for Short-Reach

Optical Interconnects'. Proc. of. ECOC, Rome, Italy, September 2018, pp 1-3.
[10] H. Yamazaki, M. Nagatani, H. Wakita, et al.: '160-GBd (320-Gb/s) PAM4 Transmission Using 97-GHz Bandwidth Analog Multiplexer', IEEE Photonics Technology Letters, 2018, **30**, (20), pp 1749-1751, DOI:10.1109/LPT.2018.2868373
[11] Nagatani, M., Wakita, H., Jyo, T., et al.: 'A 256-Gbps PAM-4 Signal Generator IC in 0.25µm InP DHBT Technology'. Proc. of IEEE BCICTS, San Diego, USA, October 2018, pp 28-31.
[12] M. Chacinski, U. Westergren, L. Thylen, et al.: 'ETDM Transmitter Module for 100-Gb/s Ethernet', IEEE Photonics Technology Letters, 2010, 22, (2), pp 70-72, DOI:10.1109/LPT.2009.2036146
[13] Buchali, F., Schuh, K., Le, S. T., et al.: 'A SiGe HBT BiCMOS 1-to-4 ADC frontend supporting 100 GBaud PAM4 reception at 14 GHz digitizer bandwidth'. Proc. of OFC, San Diego, USA, March 2019, paper Th4A.7.
[14] Ozolins, O., Pang, X., Udalcovs, A., et al.: '7×149 Gbit/s PAM4 Transmission over 1 km Multicore Fiber for Short-Reach Optical Interconnects'. Proc. of CLEO, San Jose, USA, May 2018, pp 1-2.
[15] O. Ozolins, X. Pang, M. Iglesias Olmedo, et al.: '100 GHz Externally Modulated Laser for Optical Interconnects', Journal of Lightwave Technology, 2017, **35**, (6), pp 1174-1179, DOI:10.1109/JLT.2017.2651947
[16] Jian, Y., Pfister, H. D., Narayanan, K. R., et al.: "Iterative hard-decision decoding of braided BCH codes for high-speed optical communication," Proc. of IEEE GLOBECOM, Atlanta, USA, December 2013, pp. 2376-2381
[17] M. Chagnon, S. Lessard, D. V. Plant, '336 Gb/s in Direct Detection Below KP4 FEC Threshold for Intra Data Center Applications', IEEE Photonics Technology Letters, 2016, **28**, (20), pp 2233-2236, DOI:10.1109/LPT.2016.2590983
[18] Chang, D., et al., Yu, F., Xiao, Z., et al.: 'LDPC convolutional codes using layered decoding algorithm for high speed coherent optical transmission'. Proc. of OFC, Los Angeles, USA, March 2019, paper OW1H.4.
[19] Li, X., Yu, J., Zhao, L., et al.: '132-Gb/s Photonics-Aided Single-Carrier Wireless Terahertz-Wave Signal Transmission at 450GHz Enabled by 64QAM Modulation and Probabilistic Shaping'. Proc. of OFC, San Diego, USA, March 2019, paper M4F.4.