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Published in:
Journal of Lightwave Technology

Link to article, DOI:
[10.1109/JLT.2016.2617283](https://doi.org/10.1109/JLT.2016.2617283)

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Eiselt, N., Wei, J., Griesser, H., Dochhan, A., Eiselt, M. H., Elbers, J-P., Vegas Olmos, J. J., & Tafur Monroy, I. (2017). Evaluation of Real-Time 8 x 56.25 Gb/s (400G) PAM-4 for Inter-Data Center Application Over 80 km of SSMF at 1550 nm. *Journal of Lightwave Technology*, 35(4), 955-962. <https://doi.org/10.1109/JLT.2016.2617283>

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Evaluation of Real-Time 8x56.25 Gb/s (400G) PAM-4 for Inter-Data Center Application over 80 km of SSMF at 1550 nm

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Abstract—Leveraging client optics based on intensity modulation and direct detection for point-to-point inter data center interconnect applications is a cost and power efficient solution, but challenging in terms of optical signal-to-noise ratio (OSNR) requirements and chromatic dispersion tolerance. In this paper, real-time 8x28.125 GBd dense wavelength division multiplexing (DWDM) PAM-4 transmission over up to 80 km standard single mode fiber (SSMF) in the C-Band is demonstrated. Using a combination of optical dispersion compensation and electronic equalization, results below a bit error rate (BER) of $1e-6$ are achieved and indicate sufficient margin to transmit over even longer distances, if an FEC threshold of $3.8e-3$ is assumed. Moreover, single channel 28.125 GBd PAM-4 is evaluated against optical effects such as optical bandwidth limitations, chromatic dispersion tolerance and optical amplified spontaneous emission (ASE) noise.

Index Terms—DWDM transmission, modulation, optical fiber communication, pulse amplitude modulation.

I. INTRODUCTION

DRIVEN by bandwidth hungry applications such as cloud computing, social networking or high definition TV, high speed data center interconnect applications continuous to see a tremendous growth of up to 25 % per year. To handle this demand of traffic, advanced modulation formats as well as digital signal processing and coding will play an important role in future communication systems [1], [2]. This is also vindicated by the IEEE P802.3bs Task Force, which has started to standardize four-level pulse amplitude modulation (PAM-4) as the modulation format for 400 GbE over a single mode fiber (SMF). Three optical interface classes have been defined so far: 4x50 GBd parallel fiber transmission over 500 m (400GBASE-DR4), 8x25 GBd WDM transmission with 800 GHz carrier spacing over both 2 km (400GBASE-FR8) and 10 km (400GBASE-LR8), all in the 1300 nm transmission window [3]. For such distances footprint, power consumption and cost-effectiveness are of primary concern and thus, intensity modulation and direct

detection (IM/DD) is the solution of choice.

However, there is also a high demand to move massive data within the cloud between different data center locations in the same region, forming big distributed data centers. The communication link required for this application will be referred to as point-to-point inter-data center interconnects (DCI) in the rest of the paper. Currently, no standard has been developed for these scenarios. One possible technical solution for such a system is to scale down the long-haul coherent technology, which offers high margins but incurs high cost together with high power consumption [4], [5]. Hence, there has been an increasing interest to leverage the client optics approach as a cost and power efficient solution for inter-DCI applications. In recent demonstrations, various advanced modulation formats for direct detection and dense wavelength division multiplexing (DWDM) transmission showed very high potential for such a scenario. Discrete Multi-tone (DMT) was shown in various flavours to be able to transmit over distances of more than 80 km and at data rates of more than 56 Gbit/s per channel [5]–[9]. Also carrierless amplitude and phase modulation (CAP) seems to be an interesting modulation format for such a scenario [10]–[13]. In addition, numerous publications showed PAM-4 as a possible modulation format for this application, allowing per channel data rates even up to 112 Gb/s [14]–[17]. Moreover, in several reports real-time experiments with recently developed integrated circuits (PHY) [16], [18]–[21] already indicate the feasibility of 400G transmission based on higher order modulation formats.

In [16], we showed the first real-time transmission of 8x25.78125 GBd DWDM (400G) PAM-4 in the C-band using a PAM-4 test chip-set. In this paper, the gross rate is increased to 8x28.125 GBd and demonstrated over 80 km SSMF in the C-Band. Moreover, the performance of a single channel PAM-4 signal is evaluated against several optical distortions such as

The work was in part funded by the European Commission in the Marie Curie projects ABACUS, FENDOI and CEEOLAN and by the German ministry for education and research (BMBF) under Grant 16BP12400 as part of the SASER ADVantage-Net project.

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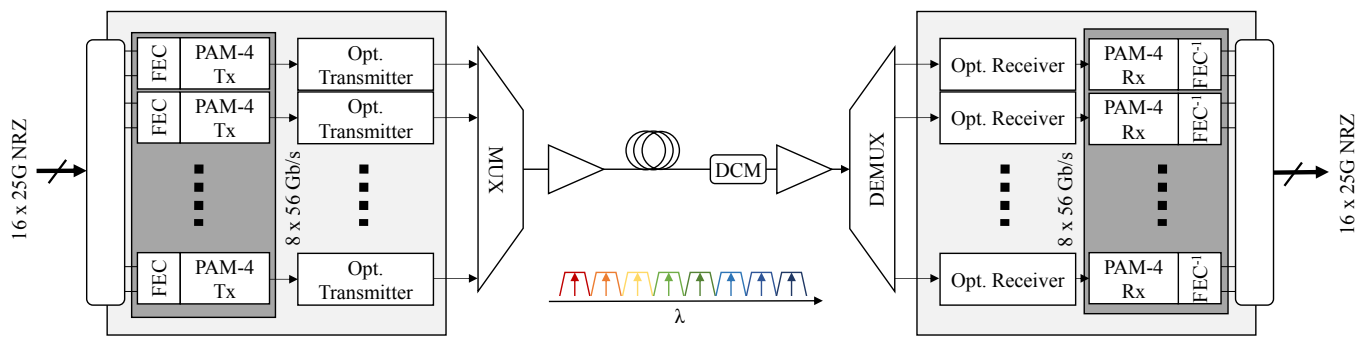


Fig. 1: Schematic of 400G PAM-4 system for inter-DCI applications (only one direction of transmission shown).

optical noise, optical bandwidth limitations and chromatic dispersion (CD). The achieved results clearly position PAM-4 as a promising option for a low-cost 400G solution for inter-DCI applications under practical OSNR requirements. Furthermore, the use of dense WDM systems represents a spectrally efficient way to scale up to multi-Tb/s DWDM links with > 4 Tb/s system capacity.

This paper is organized as follows: In section II the architecture of the point-to-point 400G inter-DCI application is presented and discussed. Afterwards, in section III, the performance of a single channel PAM-4 signal at symbol rates of 25.78125 GBd and 28.125 GBd is evaluated against different distortions and for a transmission over 80 km SSMF. Section IV reports the experimental setup and the performance of 8x28.125 GBd PAM-4 over up to 80 km SSMF. Finally, conclusions are drawn in section V.

II. POINT-TO-POINT INTER-DCI APPLICATION

Inter-DCI connections are used e.g. to connect twin data centers for business continuity and disaster recovery purposes, but also for internet content providers, and demand the movement of Tb/s of data. The transmission distance can be up to 80 km and is a point-to-point connection. As it would be extremely uneconomic to transmit only 400 Gb/s channels over a single fiber, multi-Tb/s (multiples of 400 Gb/s) DWDM links are usually deployed. Furthermore, optical booster- and pre-amplification is needed to ensure sufficient power budget. The use of DWDM enables efficient use and share of EDFAs, which work at the 1550 nm transmission window. As PAM-4 is known to be very sensitive to chromatic dispersion, the use of an optical dispersion compensating module (DCM) could be allowed, as the cost is shared between all (up to 96) channels and is thus negligible. In addition, footprint, power consumption and latency are further critical parameters which need to be considered.

In Fig. 1, the schematic of such a system is shown, with PAM-4 as one possible modulation format. To enable 400G transmission, the use of eight wavelengths at a single channel data rate of 50G per wavelength is required. Four channels with 100G per channel might also be possible; however, current bandwidth limitations of electrical components and the required OSNR favors 50G per wavelength as the more realistic solution in the short term and therefore, this will be the focus in this paper. For such a scenario, FEC is required to allow error free transmission. As we try to leverage the short-reach PAM-4 ecosystem for this scenario, it would be convenient to apply the

KR-4 or KP-4 FECs currently under consideration with 0 % and 3 % out-of-band overhead, respectively [3] (note, that an additional 2.7 % of redundancy can be allocated in-band by means of transcoding). However, there is also the option to apply an higher gain FEC, as the chip offers the possibility to run at 28.125 GBd due to overclocking. This would lead to a possible overhead of up to 9 % (and on top of it additional 2.7 % in-band transcoding overhead). Thus, we also want to consider here the FEC-BER threshold of $3.8e-3$, which requires an overhead of 7 % [22].

The latency of the described system is mainly determined by the length of the fiber. A distance of approximately 88 km (80 km SSMF + 8 km DCF) introduces a latency of approximately 422 μ s. The latency of the transceiver module is mainly determined by the used FEC, as only simple equalization is deployed. Using the KR-4 or KP-4 FEC a latency of ~ 95 ns, respectively ~ 102 ns, is introduced [23]. Using a higher gain FEC more latency is introduced.

III. SINGLE CHANNEL PAM-4

A. Experimental Setup

In Fig. 2a) and b) a block diagram of the used *Inphi IN015025-CA0* PAM-4 PHY chip and the real-time evaluation board are shown. The PAM-4 PHY chip is the same as that used in [16], [18]. At the transmitter side, a digital signal processing (DSP) unit with level shifting function and a simple, programmable feedforward equalizer are provided to compensate for limited bandwidth of the following transmitter modules. Afterwards, a digital-to-analog converter (DAC) maps the input

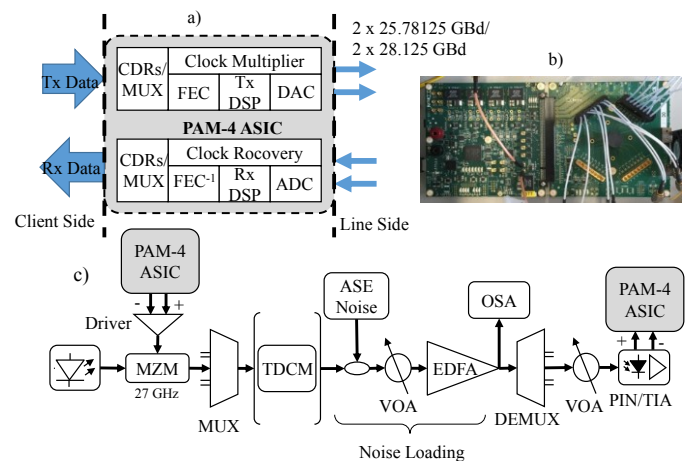


Fig. 2: a) PAM-4 transmitter and receiver IC building blocks [18], b) PAM-4 evaluation board and c) experimental setup for optical back-to-back single channel PAM-4 evaluation.

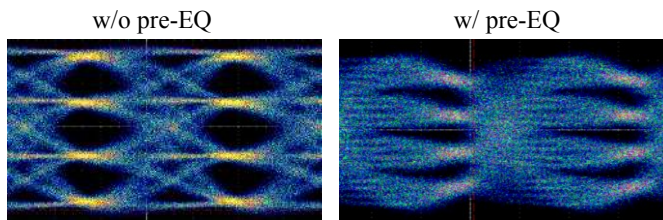


Fig. 3: 28.125 GBd PAM-4 eye diagrams at the output of the eval board without (left) and with (right) pre-equalization.

MSB and LSB (Most & Least Significant Bits) bit streams onto PAM-4 symbols. The achieved eye diagrams without and with pre-equalization for 28.125 GBd shown in Fig. 3 provide a good impression on the pre-equalization capabilities of the PHY. At the receiver side, after square-law detection, an integrated analog-to-digital converter (ADC) samples and digitizes the detected signal. Subsequently, an adaptive equalizer, a feed-forward equalizer (FFE) and decision feedback equalizer (DFE), is implemented to combat various distortions such as bandwidth limitations, chromatic dispersion and to some extent nonlinear behavior. The equalizer normally consists of 10-21 taps of FFE and 1-4 taps of DFE and the FFE part can operate at 1-2 samples per symbol [18]. All the signal processing is done in real-time and the dedicated pseudo random binary sequence (PRBS) generators and checkers within the PHY circuit are used for the PAM-4 evaluation. A PRBS of length $2^{31}-1$ is used for the experiments throughout this paper.

The experimental setup for the single channel PAM-4 evaluation is shown in Fig. 2c). The differential output of the PAM-4 eval board was amplified with a linear, differential input and single-ended output 35-GHz driver, before driving a single-ended 27-GHz LiNbO₃ Mach-Zehnder modulator (MZM). The MZM is biased at quadrature point and driven at nearly full V_{π} . The transmission frequency was set to 194.25 THz, using a tunable laser. In the optical setup, different optical effects were emulated, depending on the considered transmission scenario. Chromatic dispersion (CD) was introduced by a tunable dispersion compensating module (TDCM) with an operating bandwidth of ~ 40 GHz (specified up to 700 ps/nm CD) and full C-band CD compensation. To determine the optical signal to noise ratio (OSNR) requirement, noise was added from an amplified spontaneous emission (ASE) source to the signal via a 3-dB coupler. The OSNR was measured after the erbium doped fiber amplifier (EDFA) using an optical spectrum analyzer (OSA) and normalized to 0.1 nm. Moreover, a MUX and a DEMUX are included in the setup to emulate the bandwidth limitation of

a DWDM system. Each of the filters has an optical bandwidth of roughly 39 GHz. To measure the optical bandwidth requirements of PAM-4, the MUX and DEMUX are replaced with a variable optical filter (Waveshaper from Finisar). At the receiver, a 35-GHz bandwidth PIN-photodetector with a linear trans-impedance amplifier (PIN/TIA) from Picometrix (PT-40E) is used, while the VOA at its input controls the optical input power. Since most components for the experimental evaluation have much higher bandwidth than actually required, it can be considered as a “golden” setup providing a benchmark for the performance of PAM-4 with optical noise and to show what kind of performance with PAM-4 is achievable.

B. Receiver Sensitivity

In a first step, the measured receiver optical power sensitivity of 25.78125 GBd and 28.125 GBd PAM-4 signals in the 1550 nm transmission window is depicted in Fig. 4. For optical back-to-back (b2b) the MZM output is connected directly to a VOA, which is used to vary the input power into the subsequent 35G-PIN/TIA from Picometrix. This graph shows an optimum input power into the photodetector of around -1 dBm as well as a receiver input power window of around 5 dB, at which the BER does not change by more than a factor of 10. At an input power higher than -1 dBm the TIA gets nonlinear, resulting in a worsed BER. For less than -6 dBm input power, the increased noise from the ADC and TIA significantly degrades the performance.

C. Optical Back-to-Back

The transmission scenario of an inter-DCI application requires a pre-amplification EDFA in the transmission link and hence, a key parameter for the modulation format is its OSNR performance. In Fig. 5 the BER vs. the OSNR for the b2b case for PAM-4 at 25.78125 GBd and 28.125 GBd is shown as well as the theoretical b2b OSNR requirements of 28.125 GBd PAM-4 [24]. Furthermore, the BER limits for both FECs under consideration are depicted as dashed (KR-4 FEC, BER limit: $5.2e-5$) and continuous (FEC BER limit: $3.8e-3$) lines. For both symbol rates, less than 30 dB OSNR is required at the KR-4 FEC-threshold and less than 25 dB OSNR at $BER=3.8e-3$. The higher performance penalty for 28.125 GBd at higher OSNR is due to the stronger bandwidth limitations. At lower OSNR, the ASE-noise superimposes the bandwidth limitations; thus the penalty is less. The theoretical analysis assumes an optical matched filter receiver, considers only signal-spontaneous beat

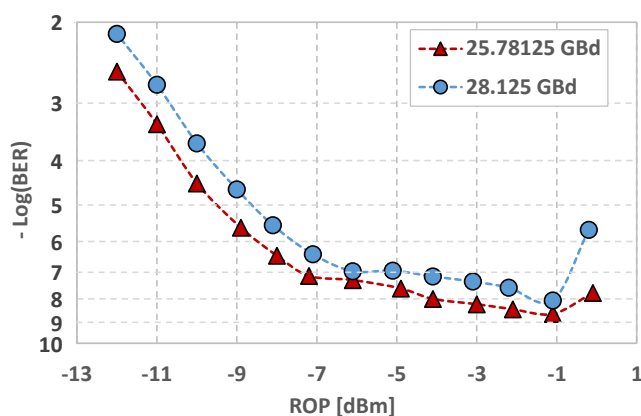


Fig. 4: Receiver sensitivity (ROP = received optical power) of 25.78125 GBd and 28.125 GBd PAM-4.

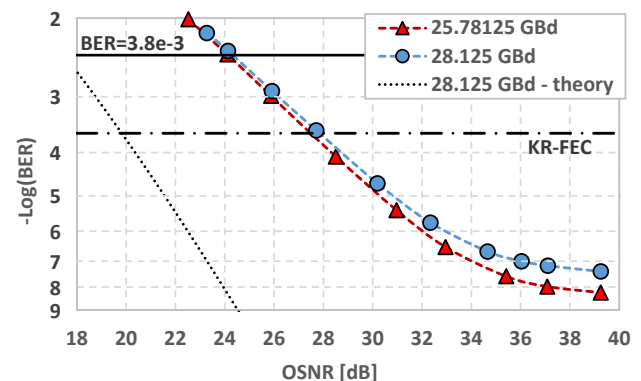


Fig. 5: Optical back-to-back performance for 25.78125 GBd and 28.125 GBd PAM-4.

noise and assumes the four intensity levels form a quadratic series [24]. In the experiment equal levels w.r.t. the optical power are used, explaining most of the 7 dB OSNR penalty between theory and measurement at BER=3.8e-3 [5].

D. Residual Dispersion

For transmission in the C-band, CD is one of the main limiting factors. The longest reach in C-band for 56 Gb/s PAM-4 without optical CD compensation has been reported as 26.4 km, enabled by non-linear filtering, decision feedback equalization and maximum likelihood sequence estimation (MLSE) [17]. Very high spectral efficiency (25 GHz channel grid) and 20 km reach was achieved with a modified single sideband (quasi SSB) Nyquist PAM-4 at 28 GBd enabled by an IQ-modulator [25]. In the following, we investigate how much residual CD can be equalized and accepted, when only a simple combination of FFE and DFE is used in the DSP. As the whole system shall be considered here, the MUX and DEMUX are left inside the system.

In Fig. 6a) and 6b) the required OSNR for 25.78125 GBd and 28.125 GBd PAM-4 transmission against residual CD values is shown at different BERs. The grayed areas mark the region of ± 170 ps/nm CD, which would relate to a transmission distance of ± 10 km SSMF at 1550 nm. At a BER of 3.8e-3, an OSNR penalty of approximately 1.5 dB at 25.78125 GBd and 1.5 dB at 28.125 GBd can be recognized. This penalty is higher at lower BERs, as in this case the CD limitations superimpose the optical ASE noise. The influence of CD scales with the square of the bitrate. Hence, 25.78125 GBd PAM-4 shows better performances at higher CD values than 28.78125 GBd. Moreover,

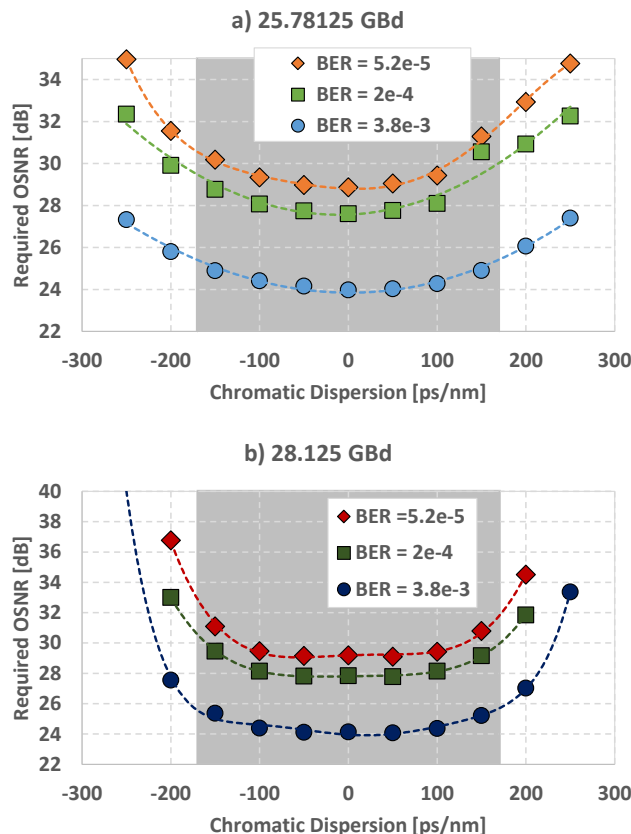


Fig. 6: Required OSNR against residual chromatic dispersion at different BERs and at a symbol rate of a) 25.78125 GBd and b) 28.125 GBd PAM-4.

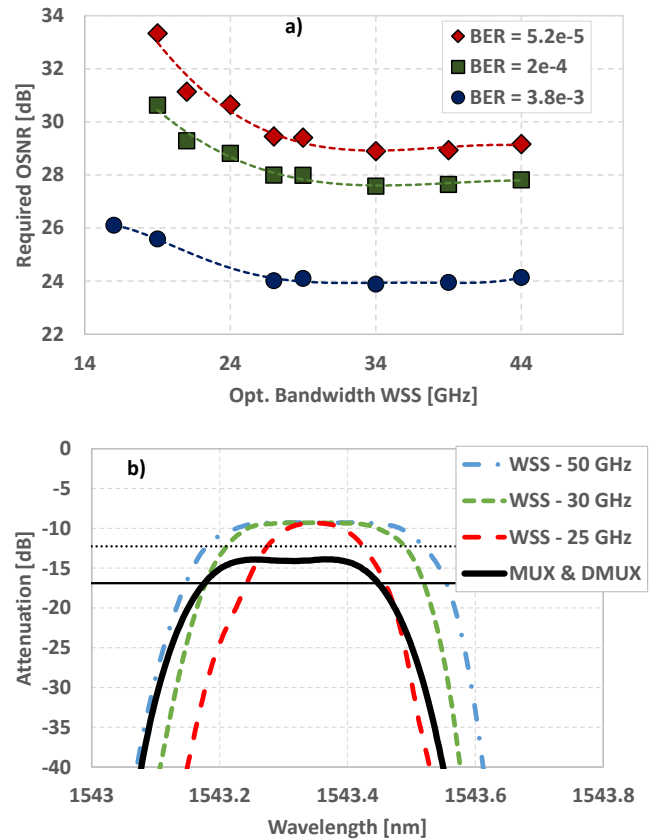


Fig. 7: a) Tolerance of 28.125 GBd PAM-4 against optical bandwidth in case a) a Waveshaper is used and b) measured frequency response of the filter at the transmission wavelength.

a small asymmetry of the curves can be recognized, because the MUX and DEMUX in the transmission system exhibit some small negative dispersion.

E. Optical Bandwidth

The tolerance of 28.125 GBd PAM-4 against the optical bandwidth is shown in Fig. 7a). For these results, the MUX and the DEMUX are replaced by a Waveshaper after the EDFA. The frequency response of several adjusted bandwidths of the Waveshaper and the frequency response of the MUX-DEMUX combination are shown in Fig. 7b) in comparison. 16 GHz optical bandwidth results in a 2 dB OSNR penalty at the BER of 3.8e-3. A 1 dB penalty is seen at about 20 GHz bandwidth. At a lower BER, this penalty appears earlier: 1 dB penalty is observed at approximately 25 GHz optical bandwidth. These results indicate, that no significant filter influence of the MUX and DEMUX is expected. This can also be verified by Fig. 7b), where a 3-dB bandwidth of the MUX and DEMUX combination of approximately 34 GHz is seen.

F. Transmission over 80 km SSMF

As discussed in section D, optical dispersion compensation is necessary in order to transmit with IM/DD PAM-4 at this symbol rate over 80 km SSMF or even over longer distances. The setup is the same as that shown in Fig. 10, considering only a single channel. Dispersion compensation options include the use of a combination of a tunable dispersion compensating module (TDCM) and a dispersion compensating fiber (DCF).

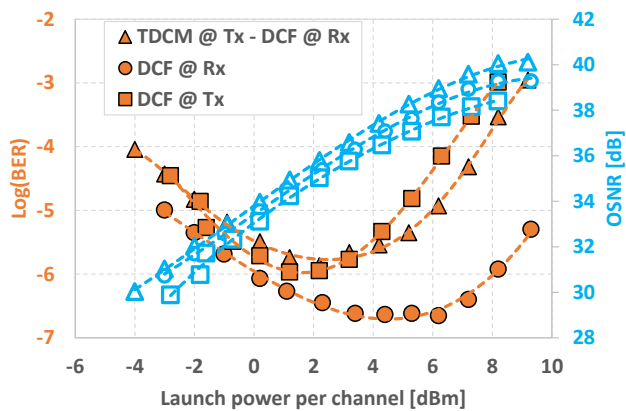


Fig. 8: BER vs. launch power (filled markers) of 28.125 GBd PAM-4 into 80 km SSF for three different scenarios of optical dispersion compensation and the achieved OSNR vs. launch power (unfilled markers).

The TDCM could be used to compensate e.g. residual dispersion of more than ± 170 ps/nm (in case of a very unmatched combination of SSF and DCF) or it could be used to compensate half of the chromatic dispersion, while the other half is compensated by a DCF. The advantage of a TDCM is the linear behavior and the lower loss compared to a DCF; however, the edges of the passband are distorted by phase ripples when compensating very high CD values. In this paper, three different scenarios are discussed: a) full pre-compensation of CD with a DCF ("DCF @ Tx"), b) full post-compensation with a DCF ("DCF @ Rx") and c) 50 % pre-compensation with a TDCM and 50 % post-compensation with a DCF matched to 40 km ("TDCM @ Tx - DCF @ Rx"). The TDCM is the same we used to determine the tolerance against residual CD in *section D*.

In a first step, the BERs for different launch powers for the three proposed scenarios are presented in Fig. 8 as filled markers. Moreover, the achieved OSNR for each launch power value and for each scenario is added to the graphic as a second y-axis (blue, unfilled markers). In case of pre-compensation, the launch power into the DCF was fixed to -5 dBm and in case of post-compensation a launch power into the DCF of approximately -3 dBm was utilized. As the DCF at the receiver was placed into the mid-stage of the second EDFA, the gain of the EDFA (20 dB to 35 dB) had to be adjusted to keep the input power into the DCF at the desired value.

At lower launch powers the transmission link is OSNR limited, while at higher launch powers nonlinearities such as self phase modulation (SPM) and stimulated Brillouin scattering (SBS) cause significant degradation of the system performance [26], [27]. From Fig. 8 a different optimum launch power and thus, different achievable BERs for each considered scenario can be seen. Full post-compensation shows the best performance in this transmission scenario, as a BER of 1.4×10^{-7} is achieved for the optimum launch power of 5.5 dBm. Pre-compensation of chromatic dispersion shows a higher vulnerability against nonlinearities, so that the BER curve rises earlier compared to post-compensation. For full pre-compensation the optimum launch power is about 1 dBm and for 50 % pre-compensation the optimum launch power is about 3 dBm. A reason for the higher sensitivity against nonlinearities might be the higher peak-to-average power ratio (PAPR) of the pre-compensated signal. Moreover, Fig. 8 shows a performance penalty of using the TDCM for 50 % pre-compensation, as a worse BER is

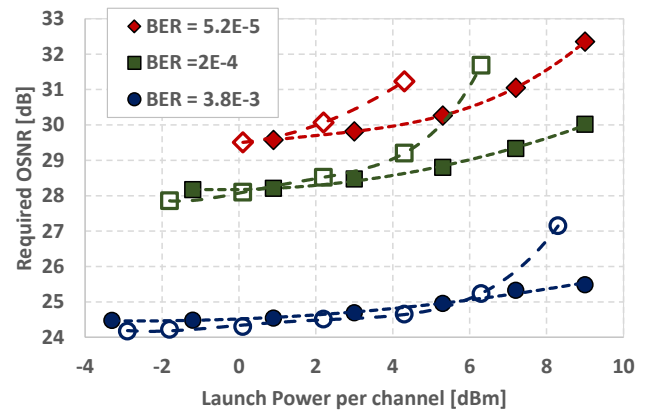


Fig. 9: Required OSNR vs. different launch powers into 80 km SSF for different BERs at 28.125 GBd PAM-4. The filled markers show the results for full pre-compensation of chromatic dispersion, while the unfilled markers show the performance of full post-compensation.

achieved compared to full pre- and post-compensation although the OSNR is similar (at lower launch power values). This is because the specified operating range of the TDCM gets smaller, the more dispersion is compensated.

Based on the results from Fig. 8, the required OSNR at different launch powers for different BERs is depicted in Fig. 9 for full pre- (unfilled markers) and post-compensation (filled markers) of chromatic dispersion. At lower input powers, both scenarios show a very similar performance, which is expected as nonlinearities do not show any significant influence. However, at higher launch powers nonlinearities come into play and such, the required OSNR for the case of pre-compensation rises earlier. Especially for the case of lower BER-values, the advantage of post-compensation is obvious. Applying post-compensation, a higher OSNR-budget can be achieved.

IV. PAM-4 OVER DWDM

A. Experimental Setup

The experimental setup for the transmission over 80 km with a single channel and also with eight channels using DWDM is shown in Fig. 10. When transmitting 400G, each of the two 27G-MZMs modulated a group of four 100-GHz spaced wavelengths, with a relative offset of 50 GHz between the two groups. Again, both modulators were biased at quadrature point and driven at nearly full V_π . After the MZMs a 50-GHz interleaver (IL) combined the two modulated four-channel groups leading to an eight-channel, 50-GHz spaced DWDM signal. In our experiments, the wavelengths ranging from 194.0 THz to 194.35 THz were used. The DWDM spectrum with channel numbers is shown in the inset of Fig. 10. A conventional 80 km SSF link was used for this experiment, representing a typical transmission distance for inter-DCI application. An EDFA, followed by a variable optical attenuator (VOA) was used to set the launch power level into the fiber. As the transmission link exhibited a loss of approximately 19 dB, a second EDFA after the transmission link was needed to ensure sufficient power into the receiver. The subsequent VOA is used to adjust the OSNR, which was measured with the help of the "on-off method" in case of DWDM transmission. As discussed in the previous section, the placement of the optical dispersion compensating module (DCM) needs to be optimized. The DCM could be either a

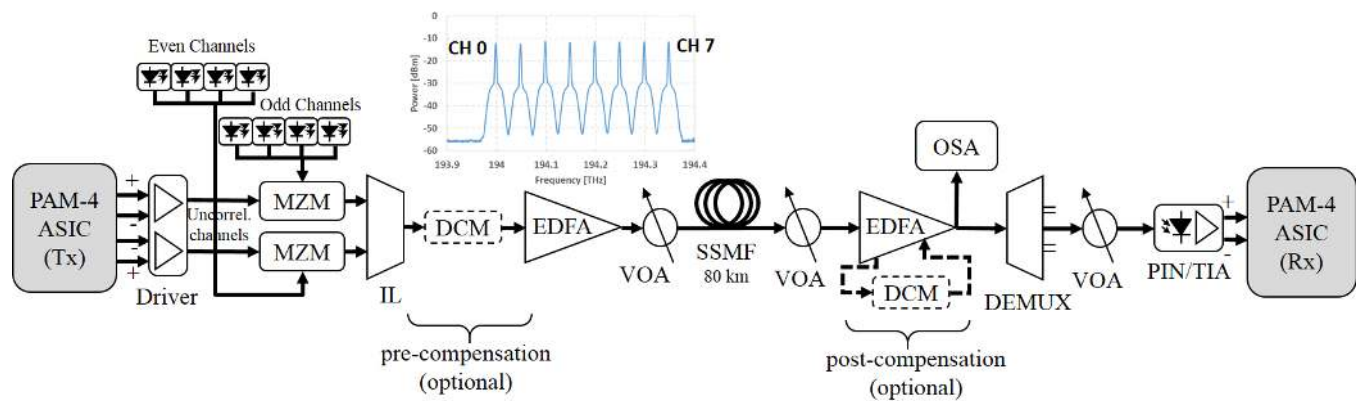


Fig. 10: Experimental setup for single channel and DWDM transmission (IL: Interleaver, EDFA: Erbium Doped Fiber Amplifier, DCM: Dispersion Compensating Module, VOA: Variable Optical Attenuator, MZM: Mach-Zehnder Modulator, PIN/TIA: PIN-photodiode with transimpedance amplifier).

DCF or a TDCM. In case of pre-compensation, the DCM was placed before the first EDFA and the input power during all transmission scenarios is set to -5 dBm. In case of post-compensation, the DCM was placed into the mid-stage of the second EDFA in order to achieve sufficient OSNR. The input power into the DCM was set to approximately -3 dBm per channel. To keep the input power constant, the gain of the EDFA is adjusted accordingly via a VOA before the DCM. Finally, the channels were separated with a DEMUX of 39 GHz optical bandwidth and a VOA controlled the power into the 35-GHz-PIN/TIA. Only one PIN/TIA was available in the lab, so that the different channels were measured consecutively.

B. Optical back-to-back

In order to determine the influence of linear crosstalk between the eight channels, the optical b2b performance of several channels of the DWDM system in comparison with the single channel performance (Single Channel MZM 1 and MZM 2) was determined and is shown in Fig. 11. In this graphic, the BER vs. OSNR results of the two single channel PAM-4 signals from the eval board for optical b2b as well as the b2b performance of channel four and channel zero of the DWDM system are shown. At the BER=3.8e-3 no significant performance differences between the single channel results and the DWDM results for optical b2b are seen, revealing a negligible impact of linear crosstalk at this symbol rate. Even at higher OSNR or lower BER ($< 1e-7$) no significant performance penalty between the single channels and the DWDM channels is recog-

nized. Some smaller differences between the two single channels of the eval board at higher OSNR are seen, which are mainly due to a different performance of the driver and the modulators.

C. Transmission over 80 km SSMF

Linear crosstalk between the channels of the DWDM system did not show a significant impact. However, transmitting over 80 km SSMF, nonlinear cross phase modulation (XPM) in addition to normal SPM comes into play and needs to be considered [26]. Hence, in Fig. 12 the BER vs. launch power per channel into 80 km SSMF is depicted for DWDM transmission (squared-marker) and for a single wavelength transmission (round-marker) at 28.125 GBd PAM-4. Again, channel number four was used here, as we expect the middle channels to suffer most from nonlinear crosstalk. Based on the results from Fig. 8 and Fig. 9, post-compensation of the chromatic dispersion was chosen. At lower launch power the link is OSNR-limited and only linear fiber distortions are present, so that no performance differences between the single channel and the DWDM channel are seen. This result is in good agreement with Fig. 11. However, at higher launch powers, the influence of XPM can be observed. The BER performance of the DWDM channel starts to degrade earlier compared to the single channel BER performance and thus, a different optimum launch power as well as a different minimum BER is achieved. The optimum launch power for a single channel is approximately 4.5 dBm while for 8 channels it is approximately 3 dBm.

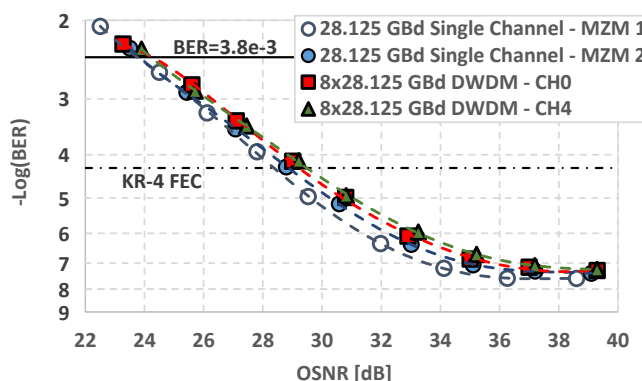


Fig. 11: BER vs. OSNR performance of 25.78125 GBd PAM-4 for optical b2b of the two single channels of the PAM-4 eval board channel four of the DWDM system.

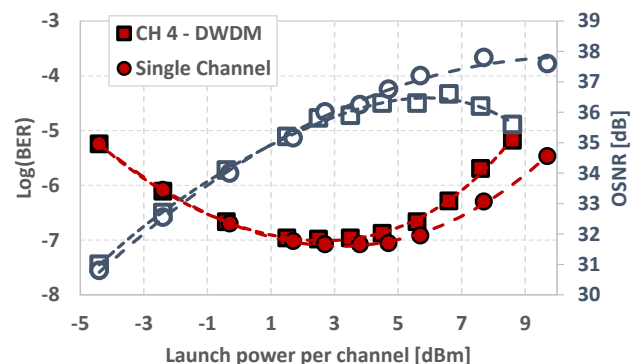


Fig. 12: BER vs. launch Power per channel for a single channel as well as for channel four of the DWDM system at 28.125 GBd PAM-4.

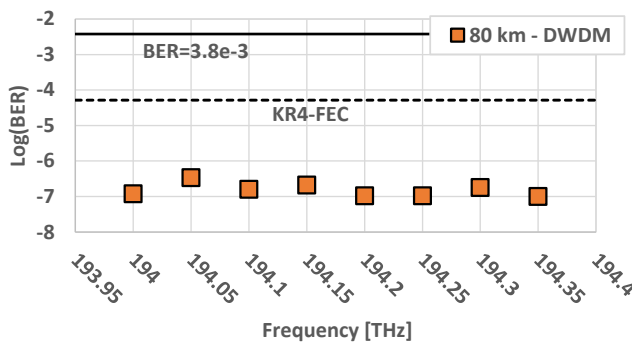


Fig. 13: DWDM performance over 80km SSMF with 28.125 GBd PAM-4 per channel.

Fig. 13 finally demonstrates the BER performance at optimum launch power (3 dBm) for all eight channels over 80 km at 28.125 GBd. All channels stay well below the FEC thresholds. Moreover, these results indicate enough margin to transmit over even longer distances than 80 km.

V. CONCLUSION

In this paper, we demonstrated real-time 28.125 GBd single channel and 8x28.125 GBd DWDM PAM-4 signal transmissions over up to 80 km SSMF in the 1550 nm transmission window. All channels stayed well below a BER of $1e-6$, indicating sufficient margin to transmit over even longer distances, if a FEC-threshold of $3.8e-3$ is assumed. The single channel PAM-4 evaluation showed a 1-dB OSNR penalty at ± 170 ps/nm chromatic dispersion, negligible effects of typical optical filter bandwidths and an optimum placement of the DCF at the receiver side. Overall, the results showed PAM-4 as a very promising low-cost, high-data rate solution for next generation of point-to-point inter-DCI applications.

ACKNOWLEDGMENT

The authors wish to thank *Inphi Corp.* for the support during the experiments.

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