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Single-lane 200G+ high speed optical transmission using single-DAC for data center interconnects

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ABSTRACT

Propelled by bandwidth-hungry cloud services, the ongoing growth of intra-datacenter traffic drives the development of high-speed short-reach transceivers, which calls for next generation optical interfaces of 800-GE or even 1.6-TbE. Conventional intensity-modulation direct-detection (IM/DD) systems still dominate the market for high speed short reach optical interconnects due to its simplicity and low cost compared with coherent solutions. Several advanced techniques to achieving net data rates around 200~250 Gbps have been demonstrated. Effective digital signal processing (DSP) for signal recovery are always used in these systems, including digital pre-distortion, digital timing recovery, feed-forward and decision feedback equalization (FFE/DFE) and stronger forward error correction. Probabilistic shaping (PS) has been introduced for 200G+ per lane IM/DD systems. Semiconductor optical amplifier (SOA) and PS can be potentially used for 200G+ per lane IM/DD systems at O-band over 10 km SMF. There are two main transmission impairments: the nonlinear impairments from the nonlinear region of the electro-optical components, and linear impairments from the bandwidth constraint of the optoelectronic devices and chromatic dispersion. Single-lane 200G+ transmission is difficult to realize due to the nonlinear impairments and the strong bandwidth constraint of optoelectronic devices. In recent years, we have experimentally demonstrated several 200G+ per lane IM/DD short-reach transmission system, making it a promising scheme for data center short-reach applications.

Keywords: Intensity-modulation direct-detection, pulse amplitude modulation, digital signal processing, data center interconnects.

1. INTRODUCTION

In the past few years, with the gradual commercialization of 5G and the promotion of data center applications, high-speed short-reach optical fiber transmission systems have aroused widespread interest. In order to meet the needs of short-reach high-speed optical communication, traditional IM/DD solutions have been challenged unprecedentedly. The bandwidth of electronic and optoelectronic devices, as well as modulation formats, coding, and digital signal processing (DSP) technology performance have all reached their limits. In this context, academia and industry have made technological breakthroughs in several areas, including the development of broadband devices, new modulation formats and coding, and high-performance DSP algorithms to overcome the above-mentioned challenges. High-speed IM/DD systems still have advantages in system cost, power consumption and package size in short-reach applications.

Wide bandwidth devices: including high-speed ADCs and modulators have been extensively studied. In the past few years, increasing the single-channel baud rate to more than 100 Gbaud has been the focus of a lot of research work. This mode of operation will definitely exceed the capabilities of the most advanced commercial digital-to-analog converters and analog-to-digital converters (DAC /ADC: 3 dB bandwidth 20-30 GHz), transimpedance amplifier (TIA: 3 dB bandwidth 30-40 GHz) and electro-optic modulator (3 dB bandwidth 40-50 GHz). In 2017, Xi Chen et al. at Nokia Bell Labs demonstrated a 100 GHz bandwidth 240-GSa/s sampling rate DAC based on digital frequency band multiplexing, and generated 190-GBaud electrical PAM-2 and PAM-4 with up to 380 Gbit/s. It was the highest symbol rate generated by the all-electric method in that year [1]. In 2017, GeSi electro-absorption modulator (EAM) and SiGe BiCMOS transmitter and receiver chipsets are integrated on a 200mm silicon optical platform, achieving 100 Gb/s NRZ-OOK transmits 500 meters of standard single-mode fiber (SSMF) and 2 kilometers of dispersion compensation fiber [2]. In 2018, a silicon-organic hybrid Mach-Zehnder modulator (SOH-MZM) for the first time is demonstrated the generation and transmission of a 100 Gbit/s OOK signal at a record low driving voltage of only 1.4 Vpp and an energy consumption of only 98fJ/bit [3]. In 2018, a 44 GHz bandwidth DFB-MZM monolithic integrated optical transmitter module based on

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InP are designed and developed using a BiCMOS DAC with a 40 GHz bandwidth and 100 GSa/s sampling rate to generate 100 GBaud NRZ, PAM-4 And PAM-8 electric drive signal, verified in C-band 100 Gbit/s NRZ and 200 Gbit/s PAM-4 to transmit 1.8 km and 1.2 km SSMF respectively [4]. In 2018, NTT reported a 100 GBaud-level InP-based IQ modulator with a bandwidth of more than 3 dB 67 GHz and a gain response of more than 60 GHz, and generation 112 GBaud 16QAM and 120GBaud QPSK optical signals [5]. In 2018, the 2:1 high-speed selector and traveling wave electro-absorption laser modulator (TW-EAM) based on InP achieved a record symbol rate of 204 Gbaud and 140 Gbaud OOK to transmit SSMF over 10 km and 80 km, respectively [6].

Advanced modulation formats: C-band DFB-TWEAM is used to successfully achieve 200 Gbit/s discrete multi-tone modulation (DMT) signal transmission 1.6 km SSMF, reaching 4.93-bit/s /Hz effective electrical spectrum efficiency in 2018 [7]. In 2017, digital pre-processing analog multiplexing digital-to-analog converter (DP-AM-DAC) is applied to generate 300 Gb/s DMT signal, and successfully transmitted 10 km SSMF in the O band, achieving a net rate of 250 Gb/s [8]. In 2019, analog multiplexers (AMUX) with> 100 GHz and 80 GHz MZM is used to achieve a net rate of 333 Gb/s DMT transmission of 20 km SSMF [9].

Novel coding: Tomlinson-Harashima precoding (THP) coding is adopted to transmit 74 GBaud precoding PAM-8 in the IM/DD system with limited bandwidth of 33GHz over 2 km SSMF with net bit rate of 185 Gb/s [10]. In 2017, the IM/DD system based on probabilistic shaping technology (PS) for the first time is demonstrated, and the result showed that the PS of 56 Gbaud -PAM-8 can reach a higher achievable information rate of 0.16 bits/symbol, which corresponds to a net bit rate increase of 8.96 Gbit/s [11]. In 2019, an integrated transmitter composed of AMUX IC and InP MZM is used to experimentally demonstrate a 162 Gbaud PS-PAM-16 transmission of 20 km SSMF, achieving a net rate of up to 400 Gb/s (total rate of 516.7 Gb/s), this is the first 400 Gb/s transmission achieved through single-carrier IM/DD using a compact transmitter [12]. In 2017, a 4D modulation based on the new Stokes vector Kramers Kronig transceiver is proposed, which transmits 60GBaud PDM-16QAM signals over 80 km SSMF in the C-band without dispersion management, achieving a single-wavelength 400 Gb/s net bit rate [13].

There are two main transmission impairments: the nonlinear impairments from the nonlinear region of the electro-optical components, and linear impairments from the bandwidth constraint of the optoelectronic devices and chromatic dispersion. Single-lane 200G+ transmission is difficult to realize due to the nonlinear impairments and the strong bandwidth constraint of optoelectronic devices. In recent years, we have experimentally demonstrated several 200G+ per lane IM/DD short-reach transmission system, making it a promising scheme for data center short-reach applications. First, single-lane EML-based IM/DD beyond 100-Gbaud 4-level pulse amplitude modulation (PAM-4) and PS-PAM-8 signals transmission over 1-km NZDSF is experimentally demonstrated based on time-domain Pre-EQ and clipping method, and 212-Gb/s PAM-4 at 7% HD-FEC threshold and 260-Gb/s PS-PAM-8 at 20% overhead FEC threshold can be realized, respectively [14]. Then, single-lane 200G and beyond IM/DD PAM transmission over 15 km SMF is experimentally demonstrated at O-band using SOA, PS and DSP, and 230 Gb/s PS-PAM8 at 7% HD-FEC threshold and 280 Gb/s PS-PAM8 at 20% SD-FEC limit can be realized [15]. Finally, single-lane 100-Gbaud PAM-8 and PS-PAM-16 signals IM/DD transmission over 1-km NZDSF with the bandwidth-limited optics using joint nonlinear equalization techniques is demonstrated, and 350-Gb/s PS-PAM-16 signal transmission can be achieved [16]. These research works demonstrated the feasibility of dual-lane 400-GbE, four-lane 800-GbE, and even eight-lane 1.6-TbE short-reach.

2. SINGLE-LANE 200G+ IM/DD TRANSMISSION SYSTEM

2.1 260 Gb/s/λ PS-PAM-8 at C-band transmission experiment based on probabilistic shaping

We first proposed a method for improving the peak-to-average ratio (PAPR) of time-domain digital pre-equalization signals based on hard-limiting probabilistic shaping. On the one hand, probabilistic shaping technology is used to obtain higher average mutual information and improve the optical signal-to-noise ratio of the system; on the other hand, time-domain digital pre-equalization technology is adopted to reduces the impact of bandwidth filtering effects caused by device bandwidth limitations. Finally, hard-limiting technology is used to reduce the PAPR of the signal and improve the overall transmission performance of the system.

The single channel 106 GBaud PAM-4 and PS-PAM-8 transmission system based on EML is shown in Figure 1. At the transmitting end, an offline Matlab® program is used to control the 106-Gsa/s BiCMOS DAC (analog 3 dB synthesis bandwidth is about 40 GHz) to generate a 106 Gbaud electrical baseband signal. An EML with a 3-dB bandwidth of 40 GHz works at an indoor temperature of 25°C, the best bias point V = -2.54 V, and the best drive current of the laser diode is 80 mA. The 106 Gbaud PAM-n signal from the DAC is first attenuated by a 6 dB attenuator, and then amplified by a commercial 60 GHz electrical amplifier to drive the EML. The purpose of the attenuator is to make the drive electrical signal work in the linear region of the amplifier to reduce non-linearity. The impact of injury. EML has a fiber-coupled output power of 6.8 dBm at a wavelength of 1538 nm. Then, a 106 Gbaud modulated optical signal is transmitted over 1 km of NZDSF, with an average dispersion coefficient of 6.4 ps/nm/km. After transmitting 1 km of NZDSF, the modulated optical signal is used to adjust the received optical power through the VOA for receiving sensitivity measurement. At the receiving end, a 70 GHz photodiode detects the signal and is amplified by another 60 GHz EA, and then collected by a real-time oscilloscope (bandwidth: 63 GHz) and processed by an offline DSP.

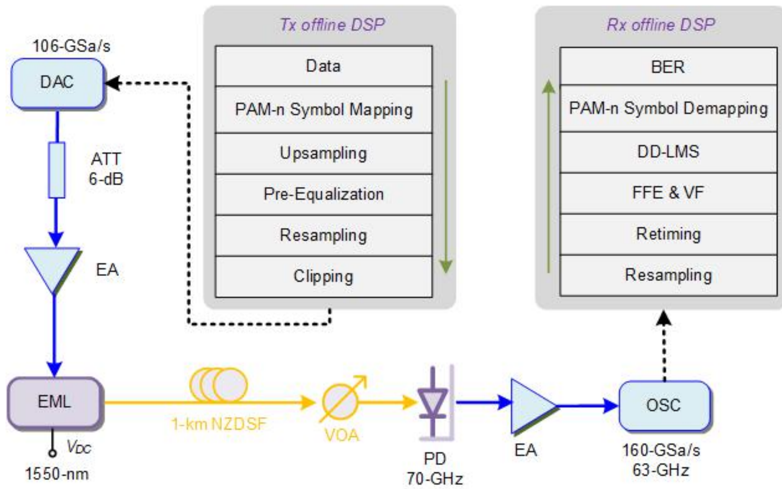

Figure 1. EML-based single-channel experimental system and offline digital signal processing flow for DCI.

At the transmitting end, after PAM symbol mapping, the symbol sequence is up-sampled to two samples per symbol. Then, based on the inverse function of the finite impulse response from the receiver-side FFE equalizer, time-domain digital pre-equalization is used to reduce the inter-symbol interference caused by the bandwidth limitation. Next, the data sequence is resampled to one sample per symbol and loaded into the DAC at the baud rate sampling rate. Before the optical fiber transmission test, estimate the pre-equalization FIR according to the transfer function of the FFE equalizer at the receiving end in the back-to-back condition. After 1 km NZDSF transmission, modulator frequency modulation and fiber dispersion are the main factors that limit fiber transmission distance. In the offline DSP at the receiving end, as shown in Figure 1, the offline data is first resampled into two samples per symbol, and then the squared clock recovery algorithm is applied to eliminate the timing offset and jitter in the data. Then, a 19-tap T/2-interval FFE, a 189-tap T-interval Volterra filter, and a 189-tap T-interval DD-LMS equalizer are used to restore the signal. Finally, the BER can be calculated after PAM-n demodulation based on the recovered signal. Before the experimental measurement, after the FFE equalizer tap coefficients converge stably in the back-to-back situation, the normalized and symmetrical processing converges the tap coefficients for the FIR filter of the time-domain digital pre-equalization.

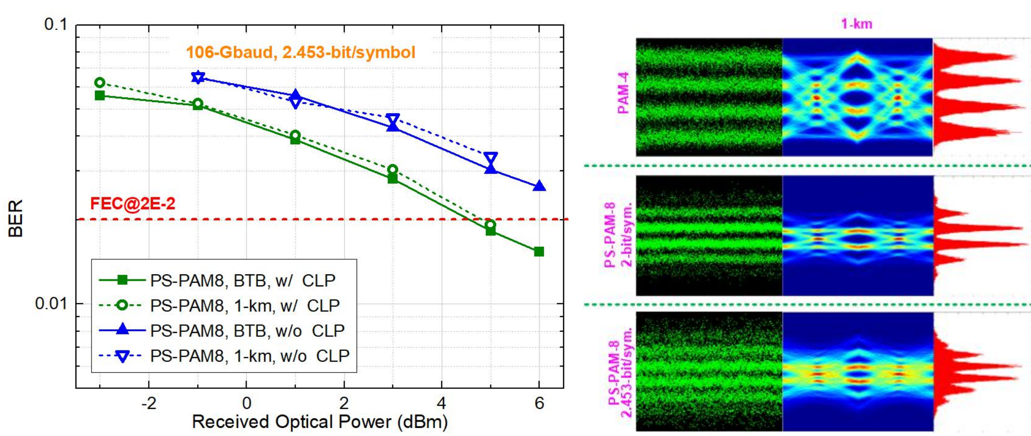

Figure 2. BER of 260 Gb/s PS-PAM-8 (2.453 bits/symbol) versus the received optical power.

By changing the shaping parameters, PS-PAM-8 symbols with three different source entropies are generated: 2 bits/symbol, 2.265 bits/symbol and 2.453 bits/symbol. Throughout the experimental test, we maintain the same total data rate (entropy × baud rate), for 106 Gbaud PS-PAM-8, the corresponding total data rate is 212 Gb/s, 240 Gb/s and 260 Gb/s. In the current research on probabilistic shaping technology, especially in long-distance coherent communication systems, NGMI is a recognized evaluation standard in the research community, and it is usually necessary to calculate the system FEC overhead and net rate. In the probabilistic shaping technology, there are two comparison methods: one is to use the same FEC overhead to compare the net rate; the other is to compare the total rate, but the FEC overhead may be different. However, it is very difficult to design FEC with different costs in the current probabilistic shaping technology. In the data center optical interconnection short-distance transmission, there is little research on probabilistic shaping technology at this stage. We assume that the use of a high-efficiency FEC system can achieve error-free transmission and compare the total transmission rate. Therefore, the experimental results are still compared with the traditional bit error rate. Perform comparative evaluation. As shown in Figure 2, we successfully achieved 260 Gb/s hard limit PS-PAM-8 (2.453 bits/symbol) transmission over 1 km of optical fiber, with a bit error rate of less than 2×10-2. Transmission of 1 km NZDSF fiber ribbon has very little effect on dispersion. At the 20% SD-FEC threshold, there will be 4dB of received optical power loss when transmitting 240Gb/s vs. 260-Gb/s PS-PAM-8 signals. The receiver sensitivity can be increased by more than 2 dB by using limiting. The hard limit method can effectively enhance the system performance of the probabilistic shaped signal after pre-equalization. For the first time, we realized single-channel optical interconnection in data centers> 200 Gb/s based on probabilistic shaping of high-level PAM signals, making it a potential option for dual-channel optical interconnection in 400 GbE data centers.

2.2 280 Gb/s/λ PS-PAM-8 transmission experiment at O-band enabled by SOA

Due to the development of high-bandwidth electronic and optical devices, it is possible to achieve single-channel 200G and higher rate transmission, which can greatly reduce the required wavelength resources and the number of required optoelectronic devices. In this section, we have verified that a single-channel 280 Gb/s PS-PAM-8 IM/DD transmission of 10 km SSMF based on SOA and PS in the O band. In the IM/DD transmission system, SOA can be placed on the transmitter or receiver. SOA can increase the output signal power of the transmitter when used at the transmitting end. Therefore, the most critical characteristic of the SOA amplifier at the transmitting end is the high saturation output power. The SOA at the transmitting end may be sensitive to polarization, because the polarization state of the input signal is known. When designing an integrated SOA device, it is necessary to design the SOA to output a large saturated output power. The SOA at the receiving end can be used as a pre-amplifier to amplify the input power into the photodetector to improve the sensitivity of the receiver. However, while satisfying the high saturation output power, the noise figure needs to be as low as possible.

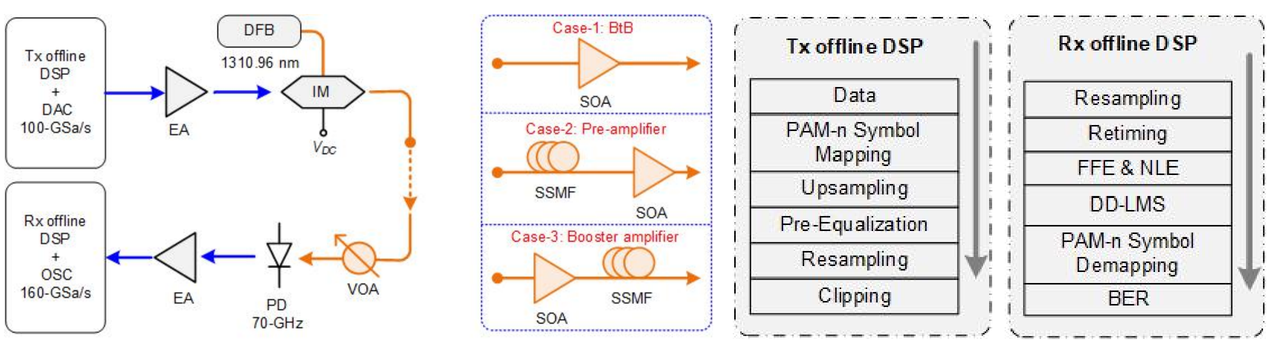

Figure 3. Experimental setup and the off-line DSP blocks at the Tx and Tx.

Figure 3 shows the installation diagram of a single-channel 100 Gbaud IM/DD PAM-N transmission system based on SOA and probabilistic shaping technology in the O band. At the transmitter end (Tx), the transmitter consists of a DFB laser with a 30 dB internal optical isolator and working at a wavelength of 1310.96 nm, an IM with a 60 GHz bandwidth, an electric amplifier (EA) with a 65 GHz bandwidth, and a high-speed DAC. The 100 Gbaud PAM-N electric drive signal is generated by a 100 GSa/s DAC (analog bandwidth 35 GHz), and then amplified by EA before driving the IM. IM works at the orthogonal point offset point, and the laser input optical power is 7.6 dBm. Three different transmission situations are considered in this experimental system: Case 1: Back-to-back case with SOA but no transmission fiber; Case 2: After the fiber is transmitted, SOA is used as a preamplifier at the receiving end; Case 3: In the transmission at the end, SOA is used as a power amplifier for optical fiber transmission. The average fiber loss at a wavelength of 1310 nm is 0.33 dB/km. Before entering the photodetector, VOA is used to adjust the received optical power for sensitivity measurement and SOA performance testing. At the receiver end (Rx), the signal is detected by a 70 GHz PD and amplified by another 65 GHz EA, and finally collected by a 160 GSa/s oscilloscope with a bandwidth of 63 GHz and processed by an offline DSP. In the off-line DSP at the transmitting end, PAM4 with equal probability and uniform distribution and PS-PAM8 with probability shaping are generated. The data Gray code maps regular PAM4 symbols with a length of 215; the PS-PAM-8 symbols with different source entropies are generated by using Maxwell-Boltzmann cloth. After using the 19-tap FFE FIR for two oversampling and digital pre-equalization, the symbol sequence is resampled to one sample per symbol and loaded into the DAC in a baud rate sampling manner. Pre-equalization processing may result in higher PAPR, especially for PS-PAM-8 signals, and system performance will be reduced. Therefore, the hard limit method is used to reduce PAPR.

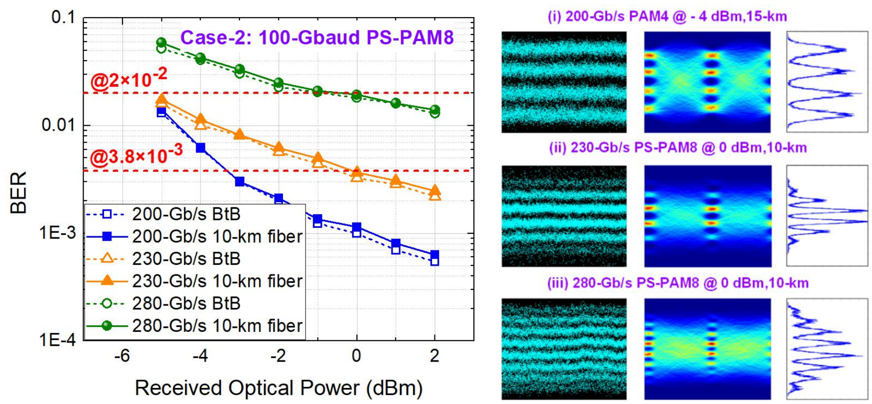

Figure 4. BER of 280 Gb/s PS-PAM-8 versus the received optical power.

We tested the relationship between the bit error rate of different PS-PAM-8 bit rates and the received optical power, as shown in Figure 4. We can see that after transmitting 10 km of SSMF, the received optical power at the FEC threshold of 200 Gb/s, 230 Gb/s and 280 Gb/s is -3 dBm, 0 dBm and 0 dBm, respectively. There is no dispersion loss between the back-to-back situation and the fiber transmission. Figure 4 illustrates the recovery symbols, eye diagrams, and amplitude statistics diagrams of 200 Gb/s PAM-4, 230 Gb/s and 280 Gb/s GPS-PAM-8, respectively. It can be seen that the level of the restored signal is equal in intervals, the eye diagram is clear, and the level and amplitude statistics are consistent with the probability density distribution of the original signal level. This is the first time to demonstrate PS technique for 200G+ per lane IM/DD over 10 km SMF fiber, making it a promising scheme for future 800 GbE and/or 1.6 TbE short-reach applications.

2.3 350-Gb/s/λ PS-PAM-16 at C-band using joint equalization techniques

Figure 5 shows a schematic diagram of the error distribution of the 50 GBaud PAM-16 received signal obtained by the intensity modulation test during the experiment, and the corresponding BER is 0.03. It can be observed that the 200 Gb/s high-order PAM-16 signal suffers more serious nonlinear damage, especially the damage at high level is more serious, and the error code is mainly concentrated on the high level side. It can also be noticed through the eye diagram that the middle-level eyes can be opened well, and the high-level eyes are blurred and closed. The observed nonlinear damage mainly comes from the nonlinear region of the intensity modulator. In addition, the inter-symbol interference between signals is also relatively large, and the linear impairment mainly comes from the limited bandwidth of the device. In order to be able to use current commercial devices to transmit higher speeds, these two types of damage need to be addressed. We propose an improved look-up table non-linear algorithm, which mainly considers the non-linearity of the high-order level of PAM, and the effect of low-level can be ignored, thereby reducing the system complexity. This reduced complexity lookup table method is particularly suitable for PAM-16 signals. The high-order PAM transmission based on probabilistic shaping technology increases the signal-to-noise ratio of the system by reducing the probability of high-order levels in the PAM signal; in order to reduce the linear damage caused by bandwidth limitation, time-domain digital pre-equalization can effectively improve and enhance the system performance; Hard clipping technology is used to further solve the problem of high PAPR caused by probability shaping and pre-equalization. Integrating our proposed joint equalization technologies such as modified look-up table, probability shaping, time-domain digital pre-equalization and hard-clipping technologies, experiments have verified the optical interconnection in a single-channel 350 Gb/s PS-PAM-16 data center.

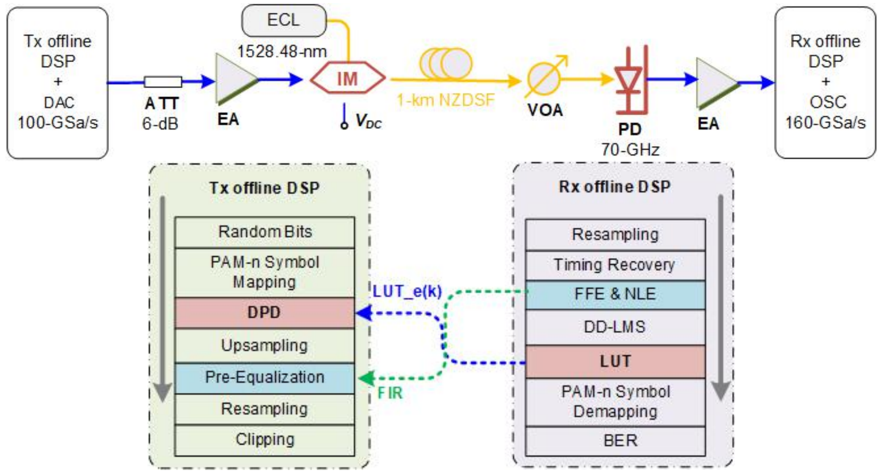

Figure 5. Experimental setup of 350-Gb/s/λ PS-PAM-16 transmission IM/DD system and offline DSP

A single-channel 350-Gb/s/λ PS-PAM-16 transmission system based on an intensity modulator, as shown in Figure 5. At the transmitting end, a 50-100 Gbaud high-order PAM signal is generated offline and downloaded to a DAC with a sampling rate of 100-GSa/s and a 3 dB analog synthesis bandwidth of 40 GHz to generate the corresponding electrical baseband signal. A commercial IM with a bandwidth of 60 GHz is used. The 1528.48 nm ECL generates a continuous light wave, and then it is input into the IM. The devices work at room temperature 25°C. Before the baseband signal drives the IM, the high-order PAM signal from the DAC is attenuated by a 6 dB attenuator, and then amplified by a commercial 60 GHz electric amplifier before driving the IM. The purpose of the attenuator is to reduce the amplitude of the output signal of the amplifier, so that the IM works in the linear region as much as possible to reduce the nonlinear damage caused by the device. Then, the modulated ultra-high-speed high-order PAM signal transmits 1 km NZDSF, with an average dispersion coefficient of 6.4 ps/nm/km. At the receiving end, before entering the photodetector, VOA is used to adjust the received optical power (ROP) for sensitivity measurement. A 70 GHz photodiode detects the signal, and then is amplified by another 60 GHz EA, and finally collected by a 160 GSa/s oscilloscope with a bandwidth of 63 GHz and processed by an offline DSP.

Before carrying out the ultra-high-speed high-order PAM transmission experiment, in order to obtain an accurate and improved look-up table pre-distortion correction value, first perform a time-domain digital pre-equalization process with a training sequence in a back-to-back situation. At a lower transmission rate, the high-order PAM training sequence without any processing is transmitted to the receiving end offline DSP for processing, and after the FFE equalizer reaches the convergence state, it can be calculated from the tap coefficients of the FFE filter for pre-equalization FIR. The look-up table pre-distortion method can effectively compensate the non-linear damage of the optoelectronic device caused by the PAM signal. After the pre-equalization process, the process of improving the look-up table is carried out. By comparing the difference between the sending training sequence and the receiving training sequence, the values are averaged multiple times and stored in the corresponding index of the look-up table. For PAM-16 signals, Only the outermost eight levels are considered. Finally, the pre-distortion correction value in the look-up table is used at the transmitter to perform nonlinear compensation.

In Figure 6, we have summarized the relationship between BER and bit rate of high-order PAM signals with different transmission rates. It can be observed that considering the SD-FEC (2×10^{-2}) threshold, the PAM-8 signal can transmit at 280 Gb/s, and the PAM-16 signal cannot reach this threshold. For the PS-PAM-16 signal, it can reach 250 Gb/s. Considering the SD-FEC (5×10^{-2}) threshold, for PAM-8 signals, due to the DAC 100-Gsa/s limitation, the highest transmission rate is 300 Gb/s. For PAM-16 signals, it can transmit 75 Gbaud, that is 300 Gb/s. For PS-PAM-16 signal, 350 Gb/s rate can be transmitted. Through the above comparison, we can see that the high-order PS-PAM-16 signal can realize the change of adaptive rate by flexibly adjusting the source entropy. Probabilistically shaped high-order PAM can well alleviate the damage caused by bandwidth-limited devices and bring higher transmission rates. We give a schematic diagram of high-order PAM recovery signals and eye diagrams at different rates. Through the PAM-16 eye diagram with equal probability of 50 GBaud, it can be seen that the low-level eye diagram is better, the high-level eye diagram is affected by nonlinearity, and the eyes are blurred and closed. The symbols of 50 GBaud and 100 GBaud PS-PAM-16 signals can be restored normally, and the eye diagram is clear.

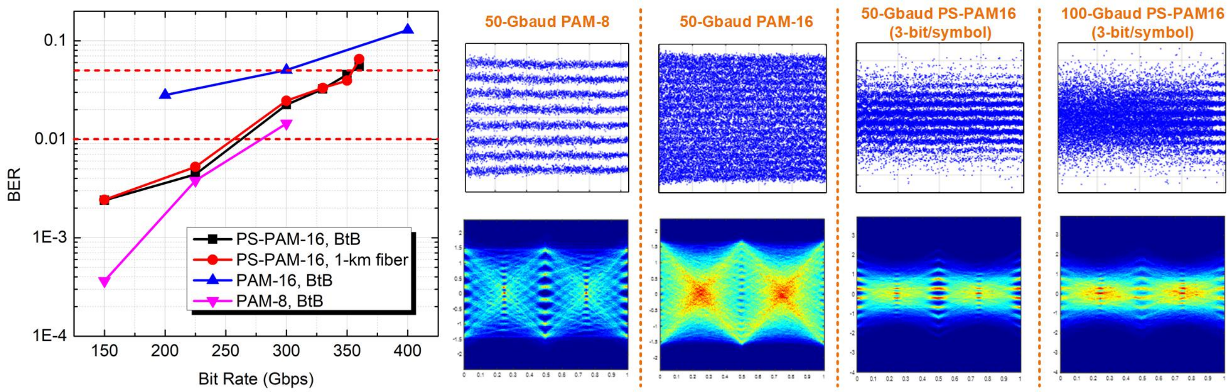

Figure 6. BER versus different bit rates.

3. CONCLUSION

For high-order PAM IMDD transmission system, we mainly did the following experimental demonstrations: First, we proposed for the first time a method for improving the PAPR of the time-domain digital pre-equalization signal based on the probabilistic shaping. Time-domain digital pre-equalization technology is used to reduce the inter-symbol interference caused by device bandwidth limitation. Hard-clipping technology is used to reduce the PAPR of the signal and improve the overall transmission performance of the system. Based on our proposed method, it is the first time to verify the single channel 260 Gb/s PS-PAM-8 signal transmission 1 km NZDSF using a single EML. Second, we analyzed the SOA large-signal gain model for ultra-high-speed signals, and the experiment verified that a single-channel 280 Gb/s PS-PAM-8 transmission of 10 km SSMF based on SOA and PS in the O band. In this system, three different transmission scenarios are compared. Because the lower SOA output power has smaller ASE noise, the receiver sensitivity of SOA when used as a power amplifier at the transmitting end is slightly better than that of SOA when used as a front end at the receiving end. However, when SOA is used as a power amplifier, it will cause a loss of received optical power. Since SOA has a higher output power, SOA is preferred to be used as a preamplifier at the receiving end. Finally, combining the improved look-up table, probability shaping, time-domain digital pre-equalization and hard-clipping technology and other joint equalization technologies, the first single-channel 350 Gb/s PS-PAM-16 is achieved. By comparing with PAM-8 and PAM-16, which are evenly distributed with equal probability, we can see the high-order PS-PAM-16 signal, which realizes the change of adaptive rate by flexibly adjusting the source entropy. Probabilistically shaped high-order PAM can well alleviate the damage caused by bandwidth-limited devices and bring higher transmission rates. We have verified through extensive experiments that high-level PAM signals based on probabilistic shaping technology achieve single-channel> 200 Gb/s data center optical interconnection, making PS-PAM a multi-channel data center that achieves 800 GbE or 1.6 TbE There are potential options for internal optical interconnection.

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