448-Gb/s PAM4 Transmission Over 300-km SMF-28 Without Dispersion Compensation Fiber

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Abstract: We report on 4×112Gb/s direct-detection PAM4 transmission over 300-km standard single mode fiber. Chromatic dispersion is digitally compensated at the transmitter side.
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1. Introduction

The growing traffic demand in inter-data center communications and metro networks requires high-capacity, low-cost, and long reach (100~300 km) optical transmission with a single-wavelength data rate of 100 Gb/s [1]. Intensity modulation direct-detection (IMDD) links using 4-level pulse-amplitude modulation (PAM4) format is very attractive due to its simplicity and low cost. However, the need for >100 km transmission distance requires system operating at the low-loss 1550 nm wavelength region, in which the fiber chromatic dispersion (CD) significantly limits the 100-Gb/s PAM4 transmission distance to about 40 km [2]. To increase the transmission distance, dispersion compensating fiber (DCF) was employed in an 8×25 Gb/s PAM4 transmission over a 100 km standard single-mode fiber (SMF-28) [3]. However, the use of DCF inevitably increases the system cost and reduces the optical signal-to-noise ratio (OSNR) after transmission. Recently, numerous techniques have been proposed to increase both reach and data rate of an SMF-28 only transmission system using direct-detection (DD). A single-wavelength net rate of 256 Gb/s discrete multitone (DMT) signal transmission over 125 km SMF-28 [4] and a 4×100 Gb/s subcarrier modulation (SCM) over 240 km SMF-28 [5] using Kramers-Kronig detection, both requiring a high oversampling ratio analog-to-digital converter (ADC) and complex digital signal processing (DSP) for the signal modulation and demodulation.

Undoubtedly, long reach systems will be more cost-effective if they can be scaled up from the short reach IMDD-based optics. For instance, transceivers based on the same 112-Gb/s PAM4 receiver design can largely reduce the device cost and shorten product development time. Comparing to DMT and SCM formats, PAM4 demodulation can be implemented using pure analog electronics, thereby has potential advantages of lower latency and energy consumption. Therefore, direct-detection PAM4 transmission over long distances is desired.

In this paper, we report on transmission of 4×112 Gb/s DD PAM4 signals over 300-km SMF-28 fiber spools and 262-km installed SMF-28 fiber link. This greatly improved transmission distance was enabled by an IQ modulator (IQM) with a phase-synchronized optical carrier inserted to the modulated signals. The CD was digitally compensated at the transmitter side, resulting in a real value intensity modulated PAM4 signal at the receiver side. This result represents the highest data rate-distance product of PAM4 transmission.

2. Operation Principle

Fig.1 shows the operation principle of our proposed system. As shown in the optical spectrum, the CD pre-compensated PAM4 signal contains a double sideband amplitude-phase modulated signal (AC component, shown blue) and an optical carrier (DC component, shown in orange) at the center. Our transmitter generates the AC component by modulating the laser light with the IQM and generates the DC component by splitting a portion of the unmodulated light and recombining it back to the modulated signals. In the DC branch, a phase shifter ensures that the carrier recombines to the modulated signal with the same optical phase, enabling a correct signal detection using DD. A variable optical attenuator (VOA) controls the carrier-to-signal power ratio (CSPR) to ensure a high extinction ratio PAM4 signal after transmission. It is worth noting that the CSPR of the CD pre-compensated signal is the same as the PAM4 signal without compensation. Therefore, the digital CD pre-compensation does not affect the required OSNR after transmission. In principle, this scheme allows pre-compensation of any deterministic impairments, such

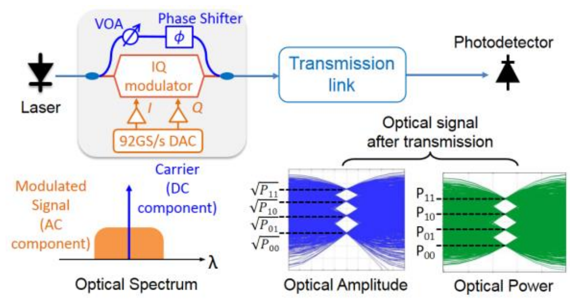

Fig.1 Operation principle of our system.

as fiber dispersion, fiber nonlinearities and electronic signal distortions due to the digital-to-analog converters (DACs) and the RF amplifiers. Thus we can transmit DD PAM4 signals over long distance without using DCF. The pre-compensated signal with optical carrier can be generated using a standard IQM by biasing it away from transmission null or using a dual-drive Mach-Zehnder Modulator (MZM) with small driving signals [6]. Our transmitter fundamentally outperforms these techniques because we can generate signals with high SNR using the linear region of the IQM. A further reduction of the transceiver cost can be achieved by using two injection-locked directly modulated lasers, as previously demonstrated in [7].

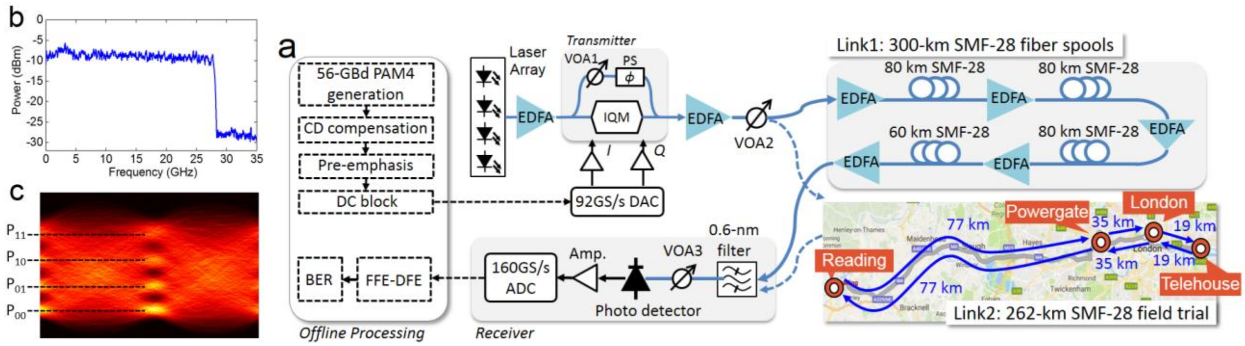

Fig. 2: (a) Experimental Setup; (b) Spectrum of the driving waveform for the CD pre-compensated 56-GBd PAM4 signal; (c) Spectrum and eye diagram of the received 56-GBd PAM4 signal. DAC: digital-to-analog converter; CD: chromatic dispersion; ADC: analog-to-digital converter; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; PS: phase shifter; IQM: In-phase and Quadrature modulator; BER: bit error ratio; FFE: feed forward equalizer; DFE: decision feedback equalizer.

3. Experimental Setup

The experimental setup is shown in Fig.2a. Four external cavity lasers (ECLs, linewidth of 100 kHz) spaced between 1548.5 nm - 1553.3 nm on a 200-GHz ITU grid were combined through a coupler and subsequently amplified to 20 dBm by an erbium-doped fiber amplifier (EDFA) before modulation. The AC component of the CD pre-compensated signal was modulated onto the optical carriers using a $LiNbO_3$ IQM biased at a transmission null. The IQ modulator was driven with two independent 92-GSample/s digital-to-analogue converters (DACs) that generate the In-phase and Quadrature components of the CD pre-compensated 56-GBd PAM4 signal. The variable optical attenuator (VOA1) adjusts the CSPR to about 11 dB.

The transmitter-side DSP consists of symbol generation, CD compensation, DC block and digital pre-emphasis. The PAM4 symbols were generated from a pseudo-random binary sequence (PRBS) of length of 2^{16}. A root-raised-cosine (RRC) filter with a roll-off factor of 1% was used to generated Nyquist-shaped 56-GBd PAM4 digital samples. CD compensation was implemented using a 128-tap finite impulse response (FIR) filter, followed by the digital pre-emphasis that compensated the frequency roll off of the DAC and the RF components. In practice, the CD compensation and the digital pre-emphasis can be realized using a single FIR filter, which further reduces the DSP complexity. After DC block, the complex digital samples of the CD pre-compensated signals were interpolated to 92 GSample/s and projected onto the real and imaginary axes to generate the corresponding In-phase and Quadrature components of the modulated signals.

The VOA2 was used to change the power launched into the two fiber links tested in the experiment. The first link consists of three spans of 80-km SMF-28 and one span of 60-km SMF-28. The 300-km fiber spools have an average loss of 0.19 dB/km and an average dispersion of about 16.3 ps/(nm·km). Four erbium-doped fiber amplifiers (EDFAs) compensated for the fiber loss. The second fiber link is a part of the UK's NDFIS dark fiber network [8], which connects London and Reading via two relay stations at Telehouse and Powergate in the UK. The installed fiber link consists of 262-km SMF-28 with an average loss of about 0.26 dB/km and an average dispersion of approximately 16.5 ps/(nm·km). EDFAs at Powergate and Reading compensated the link loss.

After transmission, the optical signal was preamplified and filtered by a 0.6-nm tunable optical bandpass filter before attenuated to 2 dBm for direct detection. The receiver comprises a 40-GHz photodetector followed by a 40-GHz RF amplifier. The electrical signal was captured by a 63-GHz, 160-GS/s ADC. The captured samples were downsampled to two samples per symbol before equalized by a 21-tap 2-sample-per-symbol-spaced feed forward equalizer (FFE) and a 1-sample-per-symbol decision feedback equalizer (DFE) with one feedback tap. The bit error ratio (BER) was calculated from 10^6 bits. The electrical spectrum and the eye diagram of the received signal are shown in Fig. 2b and Fig. 2c. An opened PAM4 eye diagram and a 28-GHz square-shaped RF spectrum without any frequency fading evidence the effectiveness of the proposed method.

3. Results

Fig.3 shows the measured BER of the transmitted signals as a function of the launch power per channel after transmission over the 300-km SMF-28 in link1. For launch power per channel higher than 1 dBm, all four channels achieved BERs below the 7% hard-decision forward error correction (HD-FEC) threshold (BER of 4.5×10^{-3}), resulting in a net rate of 100 Gb/s per wavelength and a total net data rate of 400 Gb/s. The optimal launch power was about 3 dBm. Further increasing the launch power led to a degraded performance due to fiber nonlinearity and double Rayleigh scattering. At a launch power of 3 dBm, the 1550.1 nm channel achieved an OSNR of 38 dB after transmission, resulting in a BER of 1×10^{-3}. Fig. 4 shows the BER results after transmission over the 262-km installed dark fiber link, in which the maximum launch power was 5 dBm per channel (total power of 11 dBm for four channels), limited by the maximum output power of the EDFAs in the installed fiber link. After the field trial transmission, sub-HD-FEC BER was obtained with average launch power higher than 1 dBm. At the optimal launch power of 4 dBm, BER of 8×10^{-4} was achieved for the 1550.1 nm channel. In both experiments, the CD pre-compensation was optimized for the 1550.1 nm channel, causing the performance variation between different wavelengths. In a practical system where different wavelengths are modulated with separate modulators, all four channels should achieve similar performance as the 1550.1 nm channel. The 3 dB power margin below the HD-FEC threshold allows for a practical and flexible implementation of the proposed technology in this work.

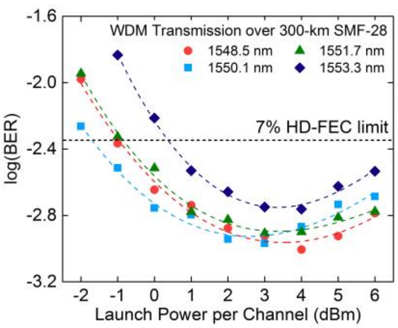

Fig. 3: Measured BER versus launch power per channel for the WDM PAM4 after transmission over 300-km SMF-28.

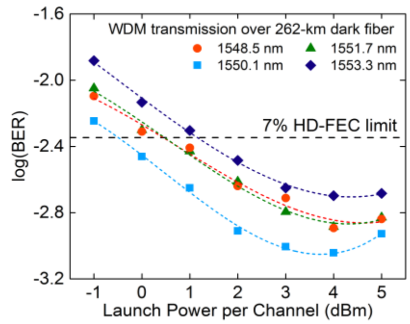

Fig. 4: Measured BER versus launch power per channel for the WDM PAM4 after transmission over the dark fiber.

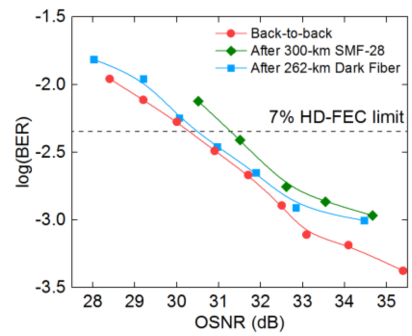

Fig. 5: BER of the 1550 nm channel at back-to-back and after transmission.

Fig. 5 shows the BER curves of the 1550.1 nm channel at different OSNRs at both back-to-back and after transmission. The required OSNR for the 7% HD-FEC threshold was about 30.2, 31.3, and 30.5 dB, at back-to-back, after the 300-km SMF-28 link and after the 262-km dark fiber, respectively. The 1.1 and 0.3 dB OSNR penalty from after transmission are due to the residual CD, polarization mode dispersion (PMD) and the phase and intensity noise of the lasers. The BER floor at high OSNR region (>33 dB) for both back-to-back and after transmission is due to the transmitter's electronic noise.

4. Conclusion

We demonstrate a net rate of 400 Gb/s transmission using direct-detected PAM4 in both 300-km SMF-28 experiment and a 262-km field trial. The proposed transmitter and CD compensation scheme allow an eight-fold increase in transmission distance for a single-lane 100-Gb/s PAM4 transmission, providing a low-cost and energy-effective solution for scaling up the reach of inter-data center communications.

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