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Experimental demonstration of 608Gbit/s short reach transmission employing half-cycle 16QAM Nyquist-SCM signal and direct detection with 25Gbps EML

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Abstract: In this paper, we experimentally demonstrated an IM/DD short reach transmission system with a total capacity of 608Gbit/s (net capacity of 565.4Gbit/s exclude 7% FEC overhead) employing half-cycle 16QAM Nyquist-SCM signal and 25Gbps EML at O band. Direct detection-faster than Nyquist (DD-FTN) technique was employed to compensate channel impairments. Number of taps of DD-LMS and tap coefficient of post filter in DD-FTN were experimentally studied for different baud rates. Single-lane 152Gbit/s transmission over 10km of SSMF was experimentally demonstrated. Employing a 4-lanes LAN-WDM architecture, a total capacity of 608Gbit/s transmission over 2km was successfully achieved with a receiver sensitivity lower than –4dBm. To the best of authors' knowledge, this is the highest reported baud rate of half-cycle 16QAM Nyquist-SCM signal and the highest bit rate employing IM/DD and 25Gbps EML in a four lanes LAN-WDM architecture for short reach systems in the O band.

OCIS codes: (060.2330) Fiber optic communications; (060.4080) Modulation.

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1. Introduction

With the fast increasing bandwidth demand of data center and other bandwidth hungry optical interconnect applications, the desired capacity of short reach transmission is expected to be 400Gbit/s or even more. Advanced modulation formats combined with coherent detection and digital signal processing has dramatically shaped the long haul optical transmission system. However, considering the form factor, power consumption and cost, intensity modulation/direct detection (IM/DD) system based on low-cost direct modulated laser (DML), electric absorption modulated laser (EML) or vertical-cavity surface emitting laser (VCSEL) combined with advanced modulation formats is a promising way to increase the system capacity while keeping system cost down. Recently, numerous advanced modulation formats based IM/DD systems have been demonstrated for high speed short reach communications.

Pulse amplitude modulation (PAM) is the simplest advanced modulation format to increase the data rate without increasing the baud-rate or bandwidth of optical device. A 100Gb/s polarization division multiplexed PAM-4 signal transmission system was demonstrated in [1]. Several high speed PAM-4 transmission systems were reported using either DML or EML [2–4]. Performances of 112Gbit/s PAM-4, PAM-8 and PAM-16 signal were demonstrated using SiP Mach-Zehnder modualtor for short reach transmission systems [5]. In our previous work, we have experimentally demonstrated single channel PAM4 signal with bit rate up to 140Gbit/s and 4-lane 500Gbit/s PAM-4 transmission system using commercial available 25G EML-TOSA and direct detection for short reach applications [6–8]. Carrier-less amplitude and phase (CAP) modulation is another option for high speed

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IM/DD transmission system. 10Gbit/s CAP-16 signal transmission over 10km was demonstrated for short reach systems [9]. Higher-order CAP signals were demonstrated for short reach applications [10, 11]. 102Gbit/s multi-band CAP signal transmission over 15km was experimentally demonstrated in [12]. Subsequently, 400Gbit/s multi-band CAP signal transmission over 20 km and 40 km of standard single mode fiber (SSMF) in O band has been reported in [13]. Discrete multi-tone (DMT) modulation also known as direct detection orthogonal frequency domain modulation (DD-OFDM), as one kind of multi-carrier modulation, is another attractive scheme for low-cost short reach communications. Single channel 101Gbit/s DMT signal transmission over 10km was achieved with a 64GSa/s AWG and a directly modulated laser [14]. More recently, 4x117Gbit/s DMT signals have been successfully transmitted over 40 km of SSMF [12]. A four-channel 560Gbit/s 128QAM-DD-OFDM short reach transmission system over 2km of SSMF was demonstrated in [15].

An alternative advanced modulation format named half-cycle M-QAM Nyquist subcarrier modulation (SCM) also attracts much interest in IM/DD short reach applications [17–19]. In our previous work, single channel 112Gbit/s half-cycle 16QAM Nyquist-SCM signal was demonstrated for short reach application employing 25G EML and direct detection [20]. In this paper, for the first time, direct detection-faster than Nyquist (DD-FTN) algorithm was applied to half-cycle 16QAM Nyquist-SCM signal in order to compensate bandwidth limitation of transmission link. With the help of DD-FTN, single lane with a bit rate up to 152Gbit/s transmission over 10km of SMF was experimentally demonstrated employing half-cycle 16QAM Nyquist-SCM signal and 25Gbps EML. Number of taps of decision directed least mean square (DD-LMS) algorithm and tap coefficient of post filter in DD-FTN were experimentally studied for different baud rate. Employing 4 lanes LAN-WDM architecture, a total capacity of 608Gbit/s (net capacity of 565.4Gbit/s with 7% FEC overhead) transmission over 2km was successfully achieved with a receiver sensitivity lower than −4dBm.To the best of authors' knowledge, this is the highest reported baud rate of half-cycle 16QAM Nyquist-SCM signal and the highest bit rate employing IM/DD and 25Gbps EML in a 4-lane LAN-WDM architecture for short reach systems in the O band.

2. Digital signal processing for half-cycle 16QAM Nyquist-SCM signal

Figure 1(a) shows the signal processing blocks at transmitter side for half-cycle 16QAM Nyquist-SCM signals. A 2^{16} de Bruijin bit sequence is used for QAM mapping and the generation of in-phase (I) and quadrature (Q) components. A raised cosine Nyquist pulse shaping filter is employed to produce two Nyquist PAM-4 signals as in-phase and quadrature signals, respectively. The I and Q components are up-converted on to a $F_s/2$ subcarrier and combined to generate the electrical half-cycle 16QAM Nyquist-SCM signal through Eq. (1).

$$S(t) = I(t) * \cos[2\pi(F_s / 2)t] - Q(t) * \sin[2\pi(F_s / 2)t] \quad (1)$$

where F_s is the baud-rate of the signal. Then generated signal is fed into a pre-emphasis filter, which compensates the limited bandwidth of DAC, RF amplifier and EML. At last, re-sampling is applied to fit the sampling rate of the DAC.

Figure 1(b) shows the digital signal processing at receiver side for half-cycle 16QAM Nyquist-SCM signal. The digital samples are normalized, down-converted and bandlimited to $F_s/2$ to separate I and Q components. Then the combined 16QAM signal was resampled to 2 samples per symbol. A digital square and filtering clock recovery algorithm is used for retiming. Two stage of linear equalization is used. A $T_s/2$ spaced modified multi-radius modulus algorithm (MMCMA) is applied for pre-convergence [9]. A T_s spaced DD-LMS is used for fine equalization. T_s is the symbol period of the received signal. The number of taps for MMCMA is fixed to 31. The optimization of number of taps of DD-LMS will be studied in section 3. In this paper, the over-all system frequency response is much smaller than the bandwidth of signal. It is well known that linear equalization would severely enhance the in-band noise of high-frequency components of signal in bandwidth limited optical transmission systems. In our previous work [8], DD-FTN algorithm is proposed to improve the performance of PAM-4 signal based IM/DD system. The DD-FTN consists of a linear equalizer, a digital post filter and maximum likelihood sequence estimation (MLSE) function. In this paper, for the first time, we apply DD-FTN to half-cycle 16QAM Nyquist-SCM signal in order to compensate bandwidth limitation of transmission link. Here, the 16QAM after linear equalization is separated into in-phase and quadrature components, which are two PAM-4 signals. Then digital post filters are employed to suppress enhanced in-band noise at high frequency components by linear equalizer for I and Q components, respectively. The frequency response of the post filter has a transfer function of $H(z) = 1 + \alpha z^{-1}$ with α as optimization parameter. The optimization process is the same as the one described in [8] and will be studied in section 3. Then, MLSE algorithm is employed to eliminate the strong inter-symbol interference (ISI) induced by the post filter, followed by symbol decisions and BER calculation by bit error counting.

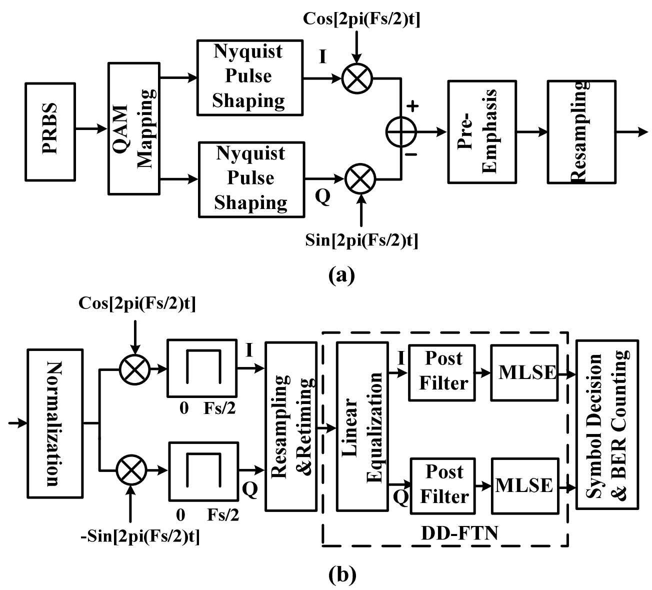

Fig. 1. (a) Transmitter DSP for half-cycle 16QAM Nyquist-SCM signal. (b) Receiver DSP for half-cycle 16QAM Nyquist-SCM signal.

3. Single-lane transmission experiment setup and results

Figure 2 shows the experimental setup for single lane transmission system. In this section, the performance of half-cycle 16QAM Nyquist-SCM signal with baud-rate (Fs) of 28GBaud, 32Gbaud and 38Gbaud are experimentally studied. Therefore, the frequencies of subcarriers (Fs/2) are 14GHz, 16GHz and 19GHz for 28Gbaud, 32Gbaud and 38Gbaud, respectively. A DAC with a 3dB bandwidth of 30GHz (Keysight M8196A) is used to generate the driving signal for transmitter. Eye-diagrams of 16QAM-SCM signal with different baud-rates were also shown in Fig. 2. It can be seen that the eye-opening decreases as the baud rate increases. However, eye-opening can still be demonstrated even with a baud rate of 38Gbaud. The electrical driving signal is amplified to a 1.78V peak-to-peak by an electric linear amplifier (SHF S807). Commercial 25Gbps EML (Neophotonics, OL3175M) with a 3dB bandwidth of 20GHz was used to modulate the signal on to the optical carrier. The bias voltage is optimized to be −1.75V. The power of output optical signal is 1dBm. A variable optical attenuator (VOA) is placed after SSMF to adjust the received optical power. At receiver side, the transmitted signal is detected by a PIN + TIA receiver with a 3dB bandwidth of 30GHz. The detected signal is sampled by a real-time scope with a sampling rate of 160GS/s and a bandwidth of 59GHz. The captured data is processed offline. The end-to-end frequency response of the whole optical transmission link is shown in Fig. 3. A 3dB bandwidth of 20GHz was demonstrated. Sharp roll off of channel response can be illustrated from 28GHz to cut-off frequency. A 10dB bandwidth of 32GHz was obtained.

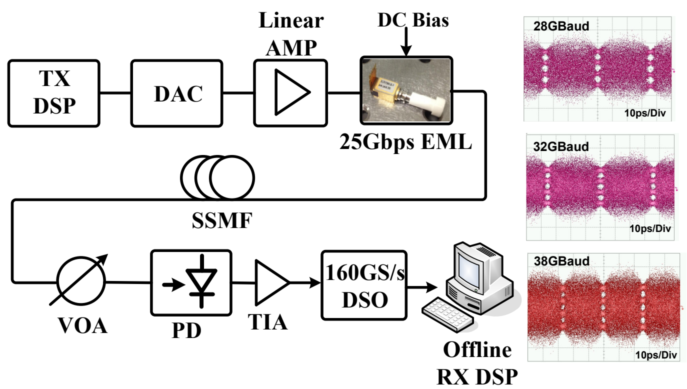

Fig. 2. Experimental setup of half-cycle 16QAM Nyquist-SCM transmission system with direct detection. DAC: digital to analog converter. Linear AMP: electrical linear amplifier. EML: electric absorption modulated laser. SSMF: standard single-mode fiber. VOA: variable optical attenuator. PD: photo detector. TIA: trans-impedance amplifier. DSO: digital storage oscilloscope.

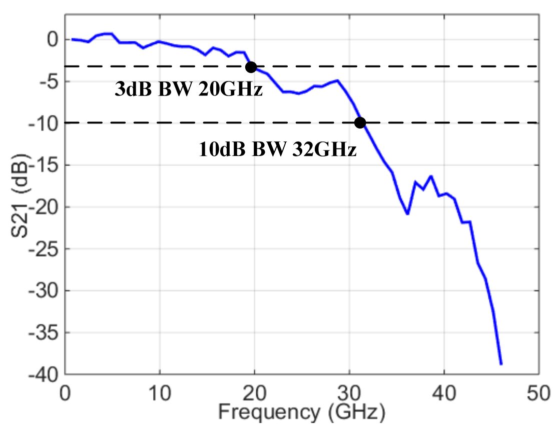

Fig. 3. The end-to-end frequency response of optical channel.

Figure 4 shows the optical spectrum at transmitter side (blue curve) and after 10km of transmission (red curve), received RF spectrum and recovered signal distributions with a launch power of –4dBm for signals with baud-rate from 28GBaud to 38GBaud, respectively. According to the received RF spectrum for signal with different baud rate, large attenuation can be seen for frequency components higher than 30GHz, which is induced by the limited end-to-end frequency response. System performance degrades as the baud-rate goes higher. A EVM of 9.1% was demonstrated for 28Gbaud/s 16QAM-SCM signal with a launch power of –4dBm in a back-to-back system. However, EVMs of 11.04% and 20.4% were obtained for 32Gbaud and 38Gbaud 16QAM-SCM signal with a launch power of –4dBm in a back-to-back system.

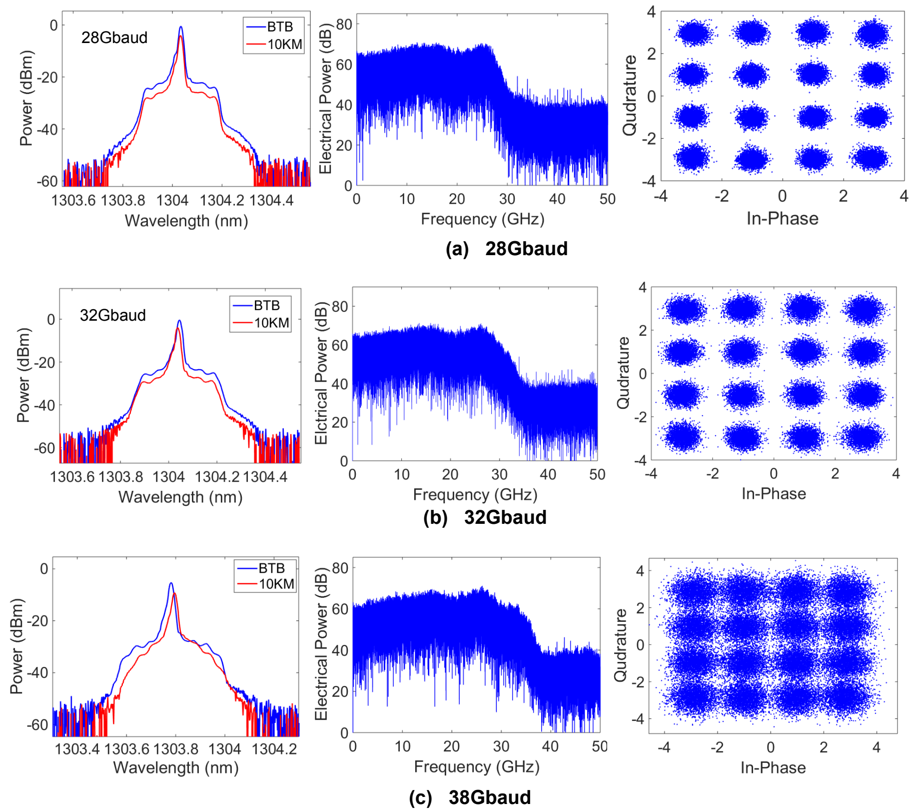

Fig. 4. Optical spectrum, received RF spectrum and recovered signal distributions with a launch power of −4dBm for different baud rates: (a) 28Gbaud; (b) 32Gbaud; (c) 38Gbaud.

As indicated in section 2, the number of taps of DD-LMS and the coefficient of the post filter should be optimized in order to facility the best performance. Figure 5(a) shows the BER vs number of taps of DD-LMS for back to back system with different baud-rate. The BER is calculated using the data directly after linear equalizer. The received optical power are −9dBm, −8dBm and −4dBm for 28Gbaud, 32Gbaud and 38Gbaud, respectively. The inset shows more details for the cases of 28Gbaud and 32Gbaud. Figures 5(b) and 5(c) show the recovered constellation of 38Gbaud 16QAM-SCM signal with a launch power of −4dBm after linear equalization with number of taps of 31 and 101, respectively. A lower BER was achieved with number of taps of 101 compared to that with number of taps of 31. It is demonstrated that lower BER can be obtained with larger number of taps for all the cases. However, the improvement introduced by increasing number of taps is not significant when the number of taps reach 51, 75 and 101 for 28Gbaud, 32Gbaud and 38Gbaud, respectively. Therefore, in order to exhibit a good balance between the complexity and performance, the number of taps of linear equalizer for 28Gbaud, 32Gbaud and 38Gbaud are set to be 51, 75 and 101, respectively. In addition, the complexity of linear equalizer can be significantly reduced by employing frequency domain equalizer (FDE) instead of time domain equalizer (TDE) [21].

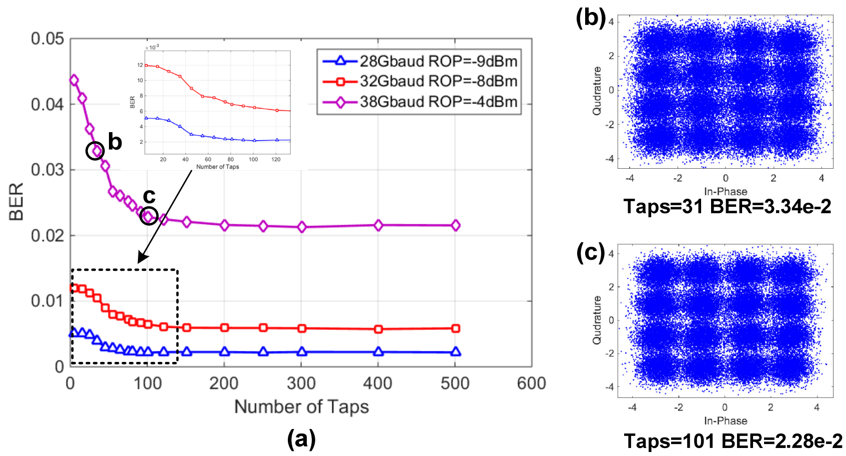

Fig. 5. (a) BER vs. number of taps of DD-LMS for different baud rates. Recovered signal distributions of 38Gbaud 16QAM-SCM signal with (b) 31 taps and (c) 101 taps.

Another important parameter in the receiver DSP module is the tap coefficient of the post filter. Figure 6(a) shows the BER vs. tap coefficient of post filter for different baud rate. The received optical power are −9dBm, −8dBm and −4dBm for 28Gbaud, 32Gbaud and 38Gbaud, respectively. It can be seen that the optimal tap coefficient increase from 0.25 to 0.65 as the baud rate increasing from 28Gbaud to 38Gbaud. Figure 6(b) shows the frequency response of post filter with different tap coefficients. It can be seen that larger tap coefficient results in lower bandwidth, sharp roll-off and larger attenuation at high frequency. Higher baud rate signal having broader spectrum would experience larger attenuation at its high frequency components. Therefore, the linear equalizer exhibits larger gain at high frequency for high baud rate signal in order to cancel the severe ISI induced by the strong filtering effects. In the meantime, the in-band noise at high frequency components in higher baud rate signal would be boosted to higher level, which results in a larger decrease of the effective SNR of the received signal. Therefore, post filter with severe filtering effect at high frequency is desired for high baud rate signal in order to suppress the enhanced in-band noise, which results in larger tap coefficients for higher baud rate signal. At last, the controllable ISI introduced by the post filter is eliminated by the MLSE.

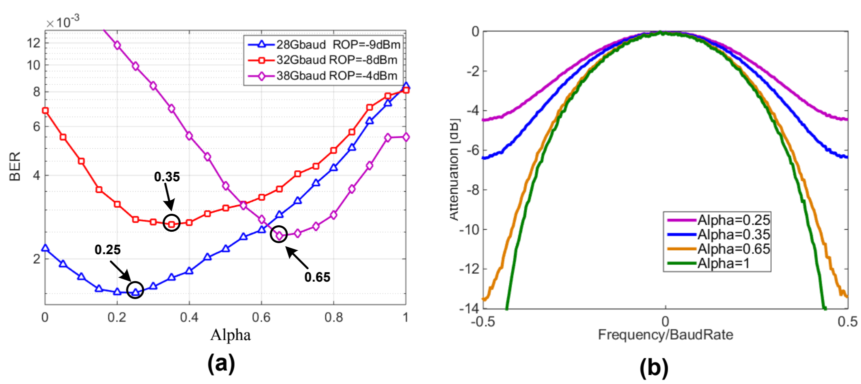

Fig. 6. (a) BER vs. tap coefficient Alpha of the post filter for different baud rate. (b) Frequency response of post filter with different tap coefficients.

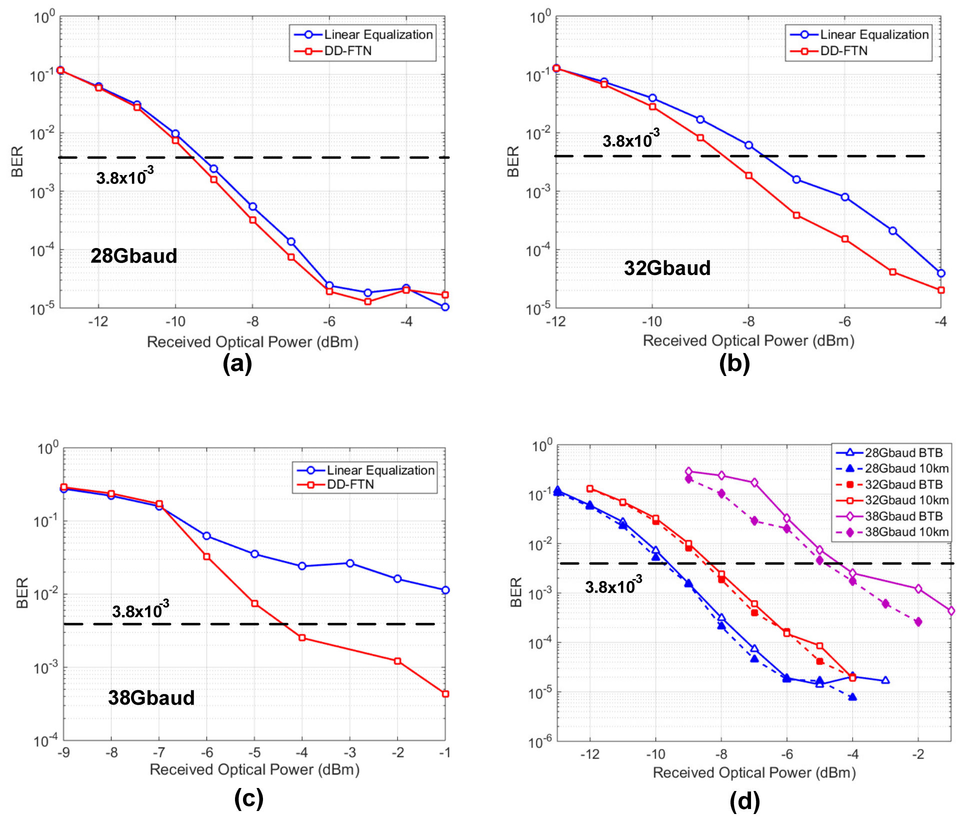

Fig. 7. (a) BER vs. received optical power for 28Gbaud back to back system with and without DD-FTN. (b) BER vs. received optical power for 32Gbaud back to back system with and without DD-FTN. (c) BER vs. received optical power for 38Gbaud back to back system with and without DD-FTN. (d) BER vs. received optical power for back to back system and after 10km transmission for different baud rates.

Figure 7(a) shows the BER vs. received optical power for 28Gbaud back- to- back system with linear equalization and DD-FTN, respectively. It can be seen that receiver sensitivities at 7% FEC overhead for BER of $3.8\text{x}10^{-3}$ are –9.2dBm and –9.6dBm for with linear equalization and with DD-FTN, respectively. An improvement of only 0.4dB in receiver sensitivity was demonstrated using DD-FTN. Figure 7(b) shows the BER vs. received optical power for 32Gbaud back to back system with linear equalization and DD-FTN, respectively. Receiver sensitivities at 7% FEC overhead for BER of $3.8\text{x}10^{-3}$ are –7.8dBm and –8.5dBm for only with linear equalization and with DD-FTN, respectively. An improvement of only 0.7dB in receiver sensitivity was demonstrated using DD-FTN. Figure 7(c) shows the BER vs. received optical power for 38Gbaud back to back system with linear equalization and DD-FTN, respectively. A BER floor around $1\text{x}10^{-2}$ was demonstrated with linear equalization, which cannot meet the pre-FEC threshold. A significant improvement can be demonstrated with DD-FTN. A receiver sensitivity of –4.4dBm was achieved by using DD-FTN at 7% FEC overhead for BER of $3.8\text{x}10^{-3}$. According the experiment results, larger improvement by using DD-FTN was investigated for higher baud rate. Higher baud signal having broader spectrum would experience larger attenuation at its high frequency components than signal with lower baud rate. Therefore, larger enhanced in-band noise would be introduced by the linear equalizer for signal with higher baud rate. The decrease of effective SNR due to the enhanced in-band noise is larger for signal with higher baud rate, which means that there is a large improvement space for higher baud-rate signal by using DD-FTN. Lower baud rate signal with small decrease of effective SNR due to the enhanced in band noise is expected to receive small improvement by using DD-FTN. Figure 7(d) shows the BER vs received optical power for back to back transmission system and 10km transmission system with baud rate of 28Gbaud (blue), 32Gbaud (red) and 38Gbaud (purple), respectively. The solid lines are for BER curves of back to back transmission and the dash lines are for BER curves of 10km transmission system. As the baud rate increasing, the required received optical power for 7% FEC threshold increases. Receiver sensitivities at 7% FEC overhead for BER of $3.8x10^{-3}$ are −9.6dBm and −9.8dBm for 28Gbaud back to back and 10km transmission system, respectively. For 32Gbaud, receiver sensitivities at 7% FEC overhead for BER of $3.8x10^{-3}$ are −8.5dBm and −8.6dBm for back to back and 10km transmission system, respectively. For 38Gbaud (152Gbit/s), receiver sensitivities at 7% FEC overhead for BER of $3.8x10^{-3}$ are −4.5dBm and −4.9dBm for back to back and 10km transmission system, respectively. No power penalty was demonstrated after transmission for all three baud rates. It can be seen that receiver sensitivities are lower for 10km transmission compared to back-to-back for all the cases. The reason is that the negative dispersion would cancel the effect of frequency chirp induced by EML, which results in better performance after transmission.

4. Four-lanes transmission experiment setup and results

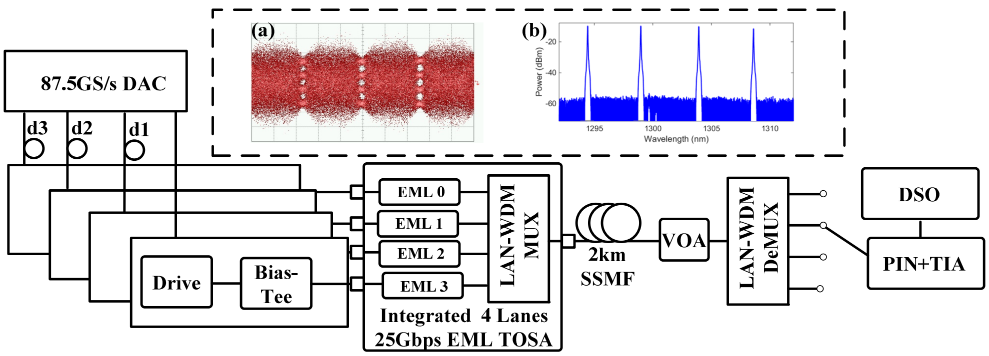

Fig. 8. Experimental setup of four channel 608Gbit/s short reach transmission system employing half-cycle 16QAM Nyquist-SCM and direct detection. DAC: digital to analog converter. EML: electrical absorption modulated laser. TOSA: Transmitter optical sub-assemble. LAN-WDM: local area network wavelength division multiplexing. MUX: multiplexer. De-MUX: de-multiplexer. SSMF: standard single mode fiber. VOA: variable optical attenuator. TIA: trans-impedance amplifier. DSO: digital storage oscilloscope. (a) Eye-diagram of Electrical 38Gbaud/s half-cycle 16QAM Nyquist-SCM signal. (b) Optical spectrum of four lanes 608Gbit/s signal.

Figure 8 shows the experimental setup for four lanes 608Gbit/s short reach transmission system employing half-cycle 16QAM Nyquist-SCM and direct detection. Four 38Gbaud (152Gbit/s) electrical half-cycle 16QAM Nyquist-SCM signals are generated by a four channel high-speed DAC (Keysight M8196A) with a sampling rate of 87.5GSam/s. The eye-diagram of generated electrical 38Gbaud half cycle 16QAM Nyquist-SCM signal is shown in Fig. 8(a). Then the four 16QAM signals are amplified to a peak-to-peak of 1.7V and used to drive an integrated 4 lanes 25Gbps EML TOSA (Neophotonics, OL3183M), which includes 4 EMLs with different wavelength and a LAN-WDM MUX. The 3dB bandwidth of 25Gbps EML is 20GHz. The bias voltages were optimized to be 1.58V, 1.7V, 1.65V and 1.7V for EML0 to EML3, respectively. A total capacity of 608Gbit/s (4x152Gbit/s) is achieved by combined the four channels with a LAN-WDM MUX. Because the insertion loss of the LAN-WDM Mux/DeMux and the limited output power of EML 0 and EML 3 (maximum 0dBm for EML0 after MUX, 0.5dBm for EML 3 after MUX), transmission distance of 2km of SSMF is considered in four-channel experiment demonstration. The center wavelengths of EMLs from

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EML0 to EML3 are 1294.5nm, 1298.9nm, 1303.8nm, and 1308.1nm, respectively. The optical spectrum of 608Gbit/s four-lane signal is shown in Fig. 8(b). Then the combined signal is launched into the 2-km transmission link. A variable optical attenuator is placed before the receiver to adjust the received optical power. The transmitted signal is de-multiplexed by a LAN-WDM de-multiplexer. The received optical power measured after De-MUX for each lane. Then the de-multiplexed signal is detected by a PIN + TIA receiver with a 3dB bandwidth of 30GHz. The detected signal is sampled by a real-time scope with a sampling rate of 160GSam/s and a bandwidth of 59GHz and the captured data is processed offline.

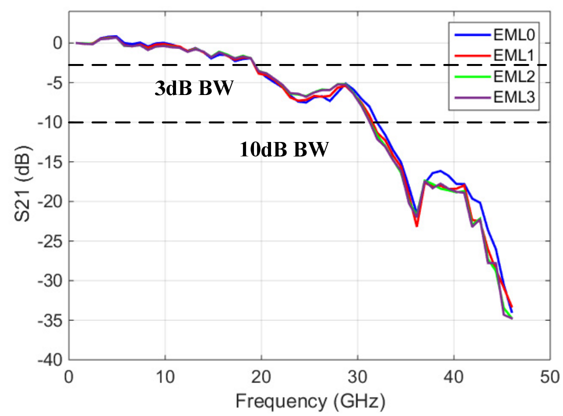

Fig. 9. The end-to-end frequency response of each optical lane.

Figure 9 show the measured end-to-end frequency responses for each optical lane. The frequency responses of the four lanes are similar. A 3dB bandwidth of 20GHz and 10dB bandwidth of 32GHz were demonstrated. Figure 10(a) shows the BER vs received optical power for the four-lane 608Gbit/s back-to-back system. Receiver sensitivities at the 7% FEC limit of $3.8x10^{-3}$ are −4.3dBm, −4.5dBm, −4.7dBm and −5dBm for EML 0 to EML 3, respectively. For 2km transmissions, the BER vs received optical power is shown in Fig. 10(b). Receiver sensitivities at the 7% FEC limit of $3.8x10^{-3}$ are −4.5dBm, −5.5dBm, −5dBm and −6dBm for EML 0 to EML 3, respectively. No power penalty is demonstrated from the transmission for all the 4 lanes. It can be seen that receiver sensitivities are lower for 2km transmission compared to back-to-back for all four lanes. The reason is that the negative dispersion would cancel the effect of frequency chirp induced by EMLs, which results in better performance after transmission. A total capacity of 608Gbit/s (net capacity of 565.4Gbit/s exclude 7% FEC overhead) was successfully achieved with a receiver sensitivity lower than −4dBm. To the best of authors' knowledge, this is the highest reported transmission capacity by using half cycle 16QAM Nyquist-SCM signal and direct detection in a 4 lanes LAN-WDM architecture for short reach systems.

Power dissipation is one of important factors for low cost short reach systems, which directly affects its practical implementation. According to the study in [22], the power dissipation can be divided into three major parts: the power dissipation of optics, thermoelectric cooler (TEC) and the CMOS power consumption. Our 4 lanes LAN-WDM approach is similar to 4x100G CAP/QAM scheme in [22] regarding system structure and modulation format (The process of Half-cycle 16QAM Nyquist-SCM is similar to CAP-16). According to the analysis in [22], it can be found that the power dissipation of our approach is quite low among 6 different schemes to realize 400G. Therefore, we believe that our approach is an energy efficient scheme to realize high capacity short reach transmission system.

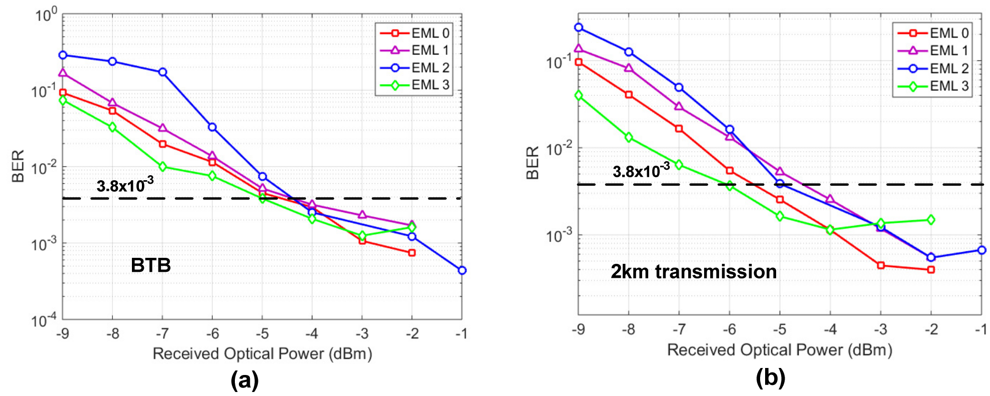

Fig. 10. BER vs received optical power for four lanes 608Gbit/s system (a) back to back transmission, (b) 2km transmission.

5. Conclusions

In this paper, an IM/DD short reach transmission system with a total capacity of 608Gbit/s (net capacity of 565.4Gbit/s exclude 7% HD-FEC overhead) was experimentally demonstrated employing half cycle 16QAM Nyquist-SCM signal and 25Gbps EML at O band. For the first time, DD-FTN technique was employed for channel impairments compensation and the achievable bit rate was increase up to 152Gbit/s per lane with 25Gbps EML. Number of taps of DD-LMS and tap coefficient of post filter in DD-FTN were experimentally studied for different baud rates. Single channel bit rate up to 152Gbit/s transmission over 10km of SMF was experimentally demonstrated. Receiver sensitivities of −9.8dBm, −8.6dBm and −4.9dBm were achieved for 112Gbit/s (28Gbaud), 128Gbit/s (32Gbaud) and 152Gbit/s (38Gbaud) at 7% FEC overhead for BER of $3.8x10^{-3}$. Employing 4-lanes LAN-WDM architecture, a total capacity of 608Gbit/s transmission over 2-km was successfully achieved with a receiver sensitivity lower than −4dBm. To the best of authors' knowledge, this is the highest reported baud rate of half-cycle 16QAM Nyquist-SCM signal and the highest bit rate employing IM/DD and 25Gbps EML in a 4-lane LAN-WDM architecture for short reach systems at O band.

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