400 Gb/s CWDM-4 PAM-4 Uncooled (22°C to 70°C) Directly Modulation Transmission over 20 km

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Abstract We demonstrate the first 400 Gb/s CWDM-4 PAM-4 transmission over a record distance of 20 km using commercial uncooled (22°C to 70°C) directly modulated lasers with tailored chirp characteristics for reach extension.

Introduction

High-speed directly modulated lasers (DMLs) are strongly demanded because this type of light source can reduce power consumption, footprint, and production cost of 100 Gb/s PAM-4 transceiver modules. Recently, a high-temperature operation of DMLs for 106-Gb/s PAM4 has been demonstrated up to 85°C over a fiber dispersion of 1.76 ps/nm [1], resulting in TDECQ of 6.6 dB. However, it is critical to demonstrate a transmission over a dispersion of ~ 4 ps/nm, corresponding to > 2 km transmission at 1330 nm to support FR4 Spec of IEEE 802.3 or even LR4 for 10 km of reach and beyond.

In order to extend the reach, the common approach is to reduce the chirp parameter. This is true for external modulators that exhibit transient chirp which is proportional to the time derivative of the intensity waveform. On the other hand, the chirp for DML is a mixture of transient and adiabatic chirp. The transient chirp component should be suppressed, however, there are various benefits for the adiabatic chirp which is proportional to the intensity waveform [2]. The first benefit is the optical duo-binary (ODB) effect [3]. When the adiabatic chirp is set to half the baud rate, namely, 25 GHz for 50 Gbaud signalling, π phase shift is introduced between 1 bits separated by 0 bit. This opens the eye by the distractive interreference between the 1 bits after transmission. Second is the dispersion supported transmission (DST) effect [4]. The third benefit is vestigial side band (VSB) effect or minimum shift keying (MSK) effect. When FM and AM are mixed with certain extinction ratio, the sidebands for AM and FM cancel each other only for the upper sideband and reduce the modulation spectrum width [5].

Another effective approach for extending the reach is to employ stronger Rx equalization and FEC scheme compared to the 5 taps FFE and KP-4 FEC scheme which are specified by the IEEE. Extending the length of Rx FFE filter can be greatly beneficial in compensating the inter-symbol interference (ISI) resulted from both the transceiver's bandwidth limitations and also from the fiber chromatic dispersion (CD).

In this paper, by setting the adiabatic chirp to ~ 25 GHz by the design of DFB laser exploiting the carrier transport and by using 81 taps FFE equalizer together with the 7% overhead FEC scheme, we demonstrate for the first time that 400 Gb/s CWDM-4 PAM4 transmission over 20 km is achievable using commercial uncooled DML (22ºC to 70ºC). This result indicates that 400 Gb/s CWDM-4 PAM4 modules with DML can be an attractive technology for edge-cloud and inter-datacenters interconnect networks.

Tailoring chirp characteristics of DFB

Tailoring the chirp characteristics by the design of DFB laser involves detailed laser physics. Adiabatic chirp originates from the gain

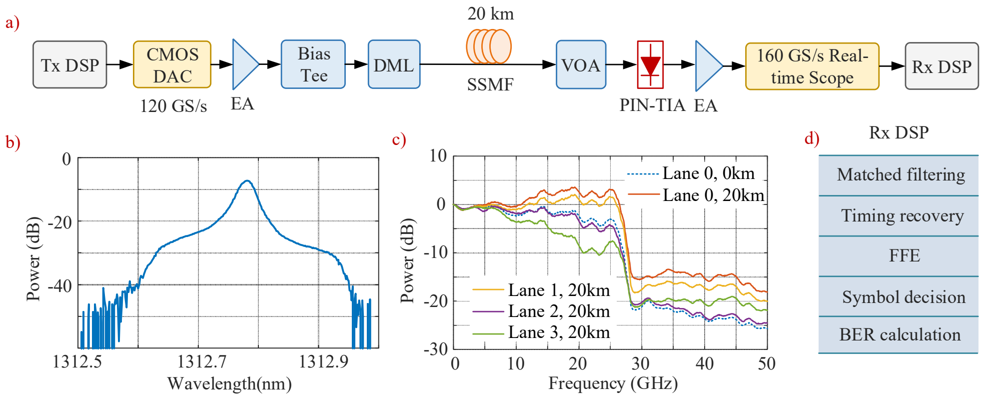

Fig. 1a) – Experimental setup: DSP – digital signal processing; EA – electrical amplifier; VOA – variable optical attenuator; b) – Optical spectrum of the lane 2 (1310 nm) at 22°C; c) – Received signal spectra for 4 lanes; d) – Rx DSP

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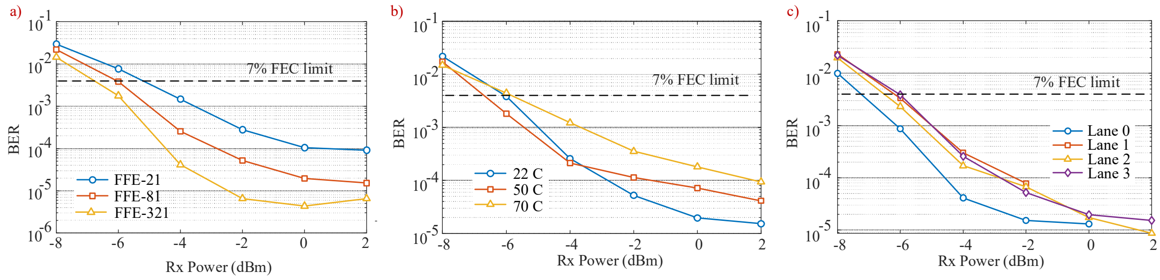

Fig. 2a) – Sensitivity of the lane 3 (1330 nm) at 22 C with various number of taps for the FFE; b) – Sensitivity of the lane 3 with FFE-81 at 22ºC, 50ºC and 70ºC; c) – Sensitivities of 4 CWDM lanes with FFE-81 at 22ºC

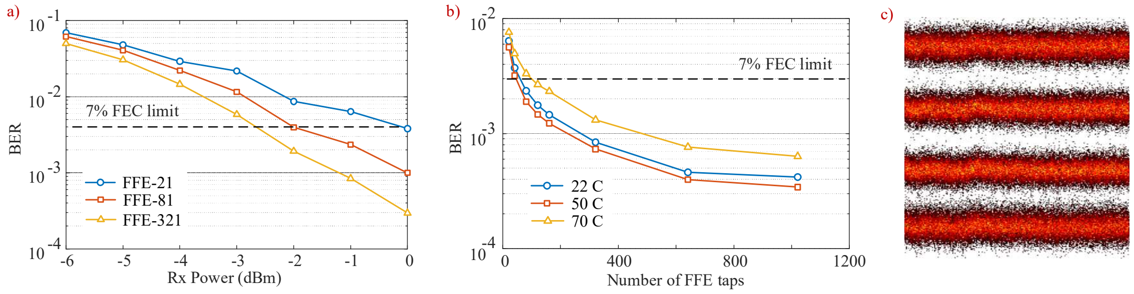

Fig. 3a) – BER versus Rx power over 20 km for the lane 3 at 22ºC with FFE-21, FFE-81 and FFE-321; b) – BER versus number of FFE taps for the lane 3 at 22ºCover 20 km with -1 dBm of Rx signal power; c) – PAM 4 constellation for lane 3 at 0 dBm and 22ºC after 20 km.

compression mechanism. The gain compression phenomena relate to any finite delay in time in the process of carrier injection [6] or spectral hole burning. The carrier transport effect is often considered as detrimental for high-speed modulation of DML, however, the moderate use of this enhances the adiabatic chirp without affecting the modulation speed. In our DFB laser design, we tailored the separate confinement layer, doping profile, and numbers of wells in the MQW structure to enhance the adiabatic chirp and suppress the transient chirp [7].

The DFB lasers used in this experiment are commercially available lasers at II-VI Inc. The DFB lasers employ the buried-hetero (BH) structure with proven reliability verified over 198 billion DFB device hours in the field since reported at OFC 2015 [7]. The 3-dB bandwidth (BW) of the DFB laser is 24 GHz, 29 GHz, and 34 GHz, at 70°C, 50°C, and 20°C, respectively.

Experimental setup and results

The experimental setup for 400 Gb/s CWDM-4 transmission is shown in Fig. 1a. At the Tx, 53.5 Gbaud Nyquist-shaped PAM-4 signal with a roll-off factor of 5% was generated offline. As shown later, Nyquist-shaped PAM-4 signal provides a better CD tolerance than the regular PAM 4 signal due to the smaller bandwidth. Next, the PAM-4 signal was loaded into the memory of a CMOS DAC running at 120 GS/s. After that, the signal at the output of the DAC was amplified by a 55-GHz electrical amplifier (EA) with a fixed gain of 23-dB. The amplified signal was then fed to a 45-GHz bias Tee for directly driving a CWDM-4 DFB laser. The DML was biased at ~ 80 mA providing an optical output power of ~ 9 dBm. The optical signal spectrum for lane 2 (centered at ~ 1312 nm) is shown in Fig. 1b. The optical signal was launched into a single span of SSMF with a span length of 20 km. The fiber has a zero dispersion at ~ 1307.6 nm and a dispersion slope of ~ 0.0897 ps/nm^2/km (at 1307.6 nm). The received electrical spectra for 4 CWDM lanes after 20 km are depicted in Fig. 1c. At the Rx, a VOA was used for adjusting the Rx signal power. The signal was detected by a 50-GHz class PIN-TIA with a gain of ~ 150 V/W. The detected signal was further amplified by another EA before being digitized by a 160 GS/s real-time scope for offline signal processing. The Rx DSP is shown in Fig. 1d which includes matched filtering after resampling to 2 samples per symbol, timing recovery and an FFE with variable number of taps.

The sensitivity measurement at the B2B for the lane 3 with 21 taps FFE (FFE-21), 81 taps FFE (FFE-81) and 321 taps FFE (FFE-321) are depicted in Fig. 2a. One can note that the sensitivity of ~ - 5dBm is achieved using FFE-21. Increasing the number of taps to 321 leads to a sensitivity increase of ~ 1.5 dB and an order of magnitude lower in BER floor. We then fixed the number of FFE taps to 81, which represents a reasonable equalization complexity and measured the sensitivities of the lane 3 when the laser chip temperature was increased to 70ºC (Fig. 2b). One can note that, the sensitivity penalty at the FEC limit is negligible. On the other hand, increasing chip temperature degrades the BER floor by an order of magnitude, which can

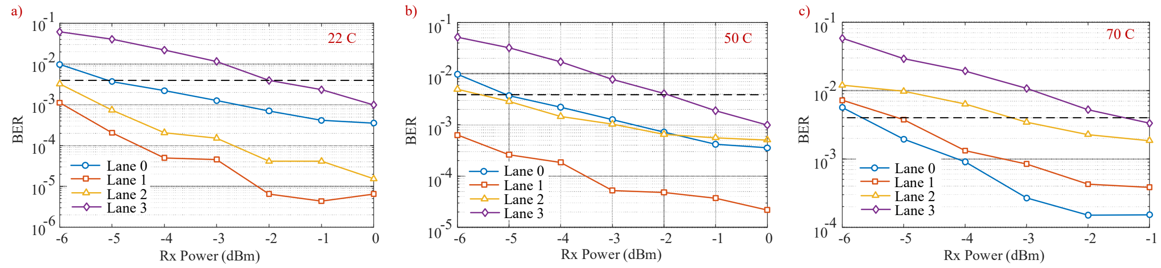

Fig. 4. Transmission performance over 20 km for all CWDM-4 lanes with FFE-81 at 22ºC (a), 50ºC (b) and 70ºC (c)

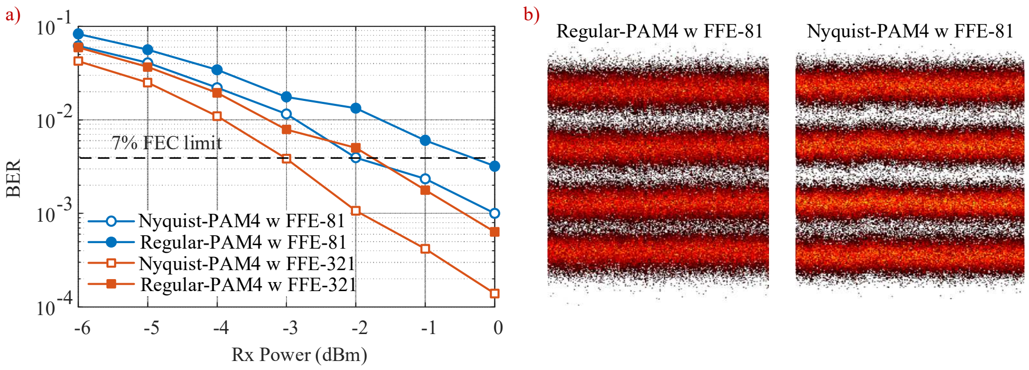

Fig. 5a Performance comparison of Nyquist PAM4 and regular PAM4 for lane 3 over 20 km at 22ºC; b) – Received PAM4 constellations at 0 dBm of Rx power

lead to a more pronounced impact on the transmission performance. The overall B2B performance for all CWDM-4 lanes at 22ºC with FFE-81 is depicted in Fig. 2c. Lane 0 shows the best performance with sensitivity of ~ -7 dBm.
The transmission performance of the lane 3 at 22ºC over 20 km is shown in Fig. 3. For lane 3 at 22ºC, the dispersion is estimated to be ~ 32 ps/nm, which can have a significant impact on the transmission performance. One can observe that with FFE-21, a BER value below the 7% FEC limit (3.8 e-3) could not be achieved with sufficient margin. When the number of FFE taps is increased to 81, a Rx signal power of -2 dBm was sufficient for achieving a BER value below 3.8e-3. Increasing further the length of the FFE can significantly improve the transmission performance as shown in Fig. 3b. Even at 70ºC, a BER below 1e-3 can be achieved if the number of FFE taps is increased to 641. This indicates that FFE can effectively mitigate the impacts of CD. On the other hand, we suspect that the long FFE was required mostly to compensate for the multipath interferences and reflections due to long RF cables and connectors used in the setup.
The overall transmission performance over 20 km for all 4 CWDM-4 lanes at 22ºC, 50ºC and 70ºC are depicted in Fig. 4, showing that BERs below FEC limit were achieved for all lanes over 22ºC to 70ºC. Herein, the number of taps for FFE was fixed at 81. One can note that unlike the similarity in the performances at B2B, the impacts of dispersion are significantly different for the 4 lanes. At 22ºC, the dispersions for lane 0, lane 1, lane 2 and lane 3 are ~ -66.3 ps/nm, -30.4 ps/nm, 8.9 ps/nm and 41.2 ps/nm. With these dispersions, lane 1 shows the best performance with at least 1 dB better in sensitivity compared to its performance in B2B. At 70ºC, due to the increased dispersion, lane 0 shows a slightly better performance than lane 1 and becoming the lane with the best performance. On the other hand, the increased in dispersion significantly degrades the performance of the lane 3 and reduces its sensitivity by ~ 1.5 dB.
Finally, we compare the performance of Nyquist-PAM4 and regular PAM4 for lane 3 at 22ºC in Fig. 5. One can note that due to the smaller bandwidth Nyquist-PAM4 provides a better tolerance to CD which leads to a better transmission over 20 km. At the FEC limit, Nyquist-PAM4 shows a ~ 2 dB higher sensitivity compared to the regular PAM4. Similar performance improvement can also be observed when FFE-321 is employed. This indicates that reducing the signal bandwidth through Nyquist pulse shaping can also improve the transmission performance.

Conclusions

We have demonstrated the first 400 Gb/s CWDM-4 PAM-4 transmission over a record distance of 20 km using commercial uncooled (22°C to 70°C) directly modulated lasers and only linear equalization at the Rx. This result was achieved through tailoring the chirp characteristics of the DFB laser and a combination of Nyquist pulse-shaping and 81 taps FFE at the Rx.

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