Tbps IM/DD Transmission over 10 km SMF with O-Band Quantum Dot Laser Comb for DCIs

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Abstract: We report a record-high Tbps DWDM transmission over 10km using a packaged 1.3 μm InAs/InGaAs quantum dot comb laser. The BER below the HD-FEC level is achieved for 1.4 Tbps PAM4 and 1 Tbps PS-PAM8 transmissions.

1. Introduction

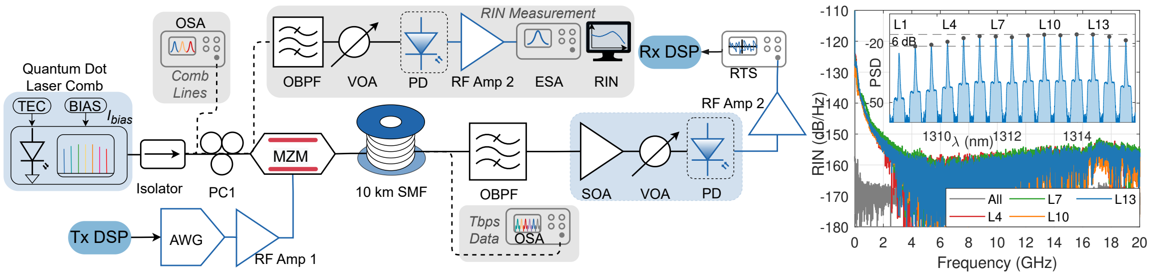
Data storage and transport in data centre (DC) networks have become enablers for many cloud and web-based applications. With the increasing demand for high-speed data transmission in both wireline and wireless networks, the need for DC bandwidth grows exponentially. The DC network topology can be categorised as intra-, campus, or inter-DC interconnects (DCI) for transmission distances of up to 2 km, 10 km, and 80 km, respectively. Closely located data centres are connected with a campus-DCI network to form a larger logical DC unit. Hence, campus-DCI links require larger bandwidth and lower latency for transmission than metro-DCI links [1]. Deploying parallel spectral channels and employing multi-level signalling at a higher symbol rate in each channel can accommodate the growing demands for short-reach systems.

High data rate intensity-modulated direct detection (IM/DD) systems are best suited for short-reach DCI links due to their backward compatibility, lower digital signal processing (DSP) complexity, power consumption, footprint, and cost. The 1.3 μm centred transmission systems present advantages compared with the 1.5 μm systems, as they offer ultra-low dispersion and robustness against power fading, especially in large bandwidth systems. To meet the data rate requirements of the DCIs, multiple parallel O-band optical carriers are suggested, which can be derived from independent laser modules or from a single optical comb source [2]. Employing multiple laser sources can increase the system's cost and power requirements [3]. Multi-wavelength optical comb sources allow dense photonic integration and can be more advantageous from a practical and economic perspective. Therefore, O-band comb sources have great potential for future short-reach and high-capacity systems [4, 5]. However, aggregated power loss due to fibre attenuation, splitting, and switching can limit the transmission performance of campus DCI links employing comb sources, requiring optical amplifiers to boost the optical signal power [6]. Semiconductor optical amplifiers (SOA) are favourable for DCIs owing to their small footprint, reduced energy consumption, and the ability for photonic integration [7].

In our previous work, we demonstrated a 100 Gbps single-channel transmission over a 10 km standard single mode fibre (SMF) using the InAs/InGaAs quantum dot in GaAs/AlGaAs material-based laser comb (QDLC) [4] and a booster SOA. In this work, by employing PAM4 and probabilistically shaped (PS) PAM8 signals, we demonstrate record-high 1.4 and 1 Tbps transmissions over 10 km, respectively, in which 14 and 10 densely-spaced lines of the QDLC are utilized with per line transmission capacity of 100 Gbps, indicating the potentials of a single-chip comb laser. To avoid the impact of nonlinear inter-channel crosstalk in a dense wavelength-division multiplexed (DWDM) system, such as four-wave mixing, and cross-gain modulation, we utilised an SOA pre-amplified receiver in the system, which enables us to maintain a low launch power into the fibre. The nonlinear distortions for PAM8 signals due to SOA nonlinearities are alleviated using probabilistic shaping (PS). The results demonstrate the potential development of a compact small-form-factor module for next-generation 800 GbE or 1.6 TbE campus-DCI links based on 1.3 μm multi-channel technology when employed with a silicon-integrated optical frequency comb modulator [8] and SOA pre-amplified receiver.

2. Experimental Setup

A standard 14-pin butterfly package houses the O-band QDLC source, which has a fixed mode spacing of about 80 GHz and is tunable over > 20 nm by changing bias and temperature. We first characterise the QDLC to measure the relative intensity noise (RIN) of the selected lines. Figure 1 (a) shows the schematic of the experimental setup for the RIN characterisation of the optical lines and the Tbps signal transmission using the QDLC. We operate the QDLC at 140 mA bias current for the experiments and maintain the operating temperature at 24.5^{o}C. Figure 1



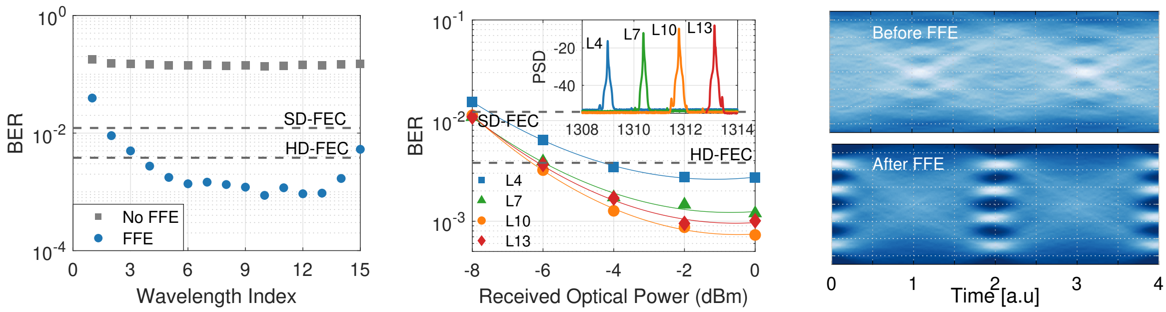
(a) (b)

Fig. 1: (a) Schematic of the experimental setup for the RIN measurements and Tbps data transmission with an O-band QDLC, (b) RIN spectrum of selected modes of QDLC at 140 mA bias current and (inset) spectrum of the modulated lines.

(b) shows the RIN for the four selected comb lines. The RIN for all lines presents a level below -160 dB/Hz. The filtered lines exhibit additional RIN at low frequency as shown in Fig. 2 (b) due to mode partition noise (MPN) before the RIN falls below -150 dB/Hz after 1.8 GHz.

We demonstrate a system-level Tbps transmission with 50 GBd PAM4 (14 lines) and 37.5 GBd PS-PAM8 (10 lines) with the QDLC, in which the signals are generated offline. For the PS, we generate the Maxwell-Boltzmann distribution-based PAM8 symbols [9] with the entropies of 2.41, 2.676, 2.88 and 3 (uniform distribution, UD) bits/symbol. The amplitude levels are pre-distorted to accommodate the nonlinear response of the external modulator. We then employ a root-raised cosine (RRC) filter with a roll-off factor of 0.1 to reduce the signal bandwidth and load it to a 32 GHz arbitrary waveform generator (AWG). An RF amplifier (RF Amp 1, 23 dB gain) amplifies the generated analogue signal from the AWG. A 30 GHz O-band Mach-Zender modulator modulates all the lines of the QDLC with the amplified PAM4/PS-PAM8 electrical signal. The inset of Fig. 1 (b) shows the optical spectrum of 15 modulated lines (80 GHz comb line spacing combined with the RRC filter of the signals ensures there is negligible interference between the channels), with indexing starting from L1 (line 1) and exhibits a 6 dB flatness over 14 lines. This $>$ Tbps PAM4/PS-PAM8 modulated data is transmitted over a 10 km SMF at $\sim$4 dBm launch power. At the receiver end, we filter each modulated line using an optical bandpass filter (OBPF) and amplify it using an SOA preamplifier. The optical power of the filtered lines at the input to the SOA (150 *mA* bias current) varied from -8 dBm to -14 dBm, depending on the selected line. To study the performance at different received optical power (*Prx*), we use a variable optical attenuator (VOA). This signal is then detected using a 30 GHz photodetector (PD), amplified using a 24 dB gain RF amplifier (RF Amp 2) and digitised using a 33 GHz real-time scope (RTS, 100 GS/s).

3. Results and Discussion



(a) (b) (c)

Fig. 2: BER performance of 50GBd PAM4 signals after 10 km SMF as a function of (a) wavelength index (with and w/o FFE) and (b) received optical power for selected lines, and (c) eye diagram of the L10 signal at -2 dBm *Prx* before and after FFE.

In the receiver-side offline DSP, we first resample the received signal and perform matched filtering with the RRC prototype filter. We then employ a linear transversal feed-forward equaliser (FFE) with 40 T-spaced taps. We use a larger tap size to reduce the effect of component-induced ISI due to their non-flat response in the desired bandwidth and not for any dispersion compensation. Figure 2(a) shows the BER performance of 1.4 Tbps PAM4 signals after 10km transmission as a function of the filtered channel wavelength index at a fixed *Prx* of -2 dBm. The performance of lines from index numbers 4 to 14 (total 1 Tbps data rate) attains a BER below the HD-FEC limit of 3.8×10^{-3} with 7% overhead. The BER performance of all the lines from L2 to L15, constituting a total data rate of 1.4 Tbps, is under the SD-FEC limit of 1.2×10^{-2} with 14.8% overhead [10]. The degraded performance in the outer channels is due to the lower input signal power to the SOA, translating to additional ASE in these channels. Figure 2(b) shows the BER performance as a function of *Prx* for selected line indices (spectrum of the filtered channel is shown as inset), and the performance falls within the SD-FEC limit for *Prx* >-7.5 dBm. Figure 2(c) shows the eye diagram of the signal (L10, -2 dBm *Prx*) with and without FFE. We then evaluate the

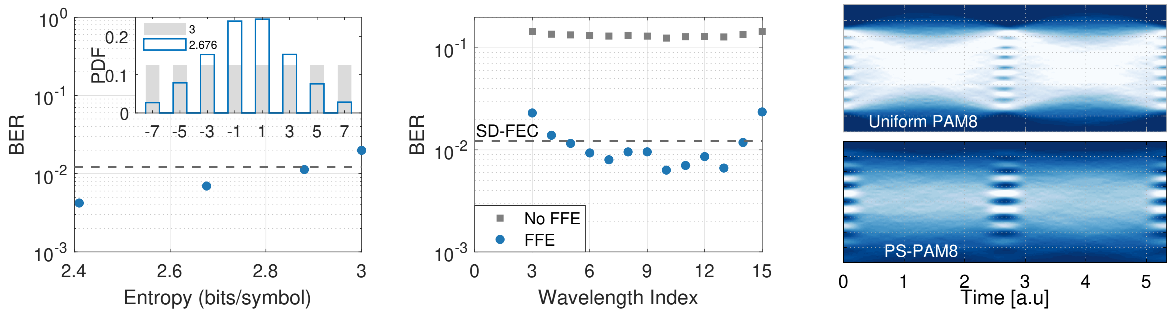


Fig. 3: BER performance of 37.5 GBd PS-PAM8 signals after 10 km transmission as a function of (a) various entropies and (b) wavelength index (2.676 entropy), and (c) eye diagram of the UD and PS-PAM8 signal of channel L10 at *Prx* = -2 dBm.

performance of the 10 km transmitted PS-PAM8 signals for the choice of entropies values for the L10 channel at -2 dBm *Prx* and Fig.3(a) shows the BER performance. We observe for an SOA preamplified system, the UD-PAM8 signal couldn't reach the SD-FEC level BER performance due to MPN and noise and distortions from SOA, and hence, we employ PS-PAM8 signal with 2.676 entropy as the best-fit choice for optimum performance and data rate. Figure 3(b) shows each filtered channel's BER performance of the 37.5 GBd PS-PAM8 signals at 0 dBm *Prx*. The performance of lines from index numbers 4 to 14 (total 1 Tbps rate) attains a BER below the SD-FEC limit. Figure 3(c) shows the eye diagram of the processed uniform and PS-PAM8 signals, evaluated at -2 dBm *Prx* after 10km transmission. The larger eye width in the case of the PS-PAM8 compared to the UD-PAM8 (at the same symbol rate) signal indicates a larger resilience to noise and SOA nonlinearity.

The above results demonstrate the potential use of the QDLC for generating multiple wavelength channels for spectrally efficient data transmission in campus-DCI links. The poor performance of certain lines can be improved by appropriately boosting the carrier power before modulation or employing SOAs with a wider dynamic range. Also, using nonlinear equalisers and machine learning algorithms can improve the performance of higher-order PAM signals in the presence of SOA nonlinearity [11]. It is also worth noting that for systems employing low bandwidth components (<20 GHz), the data rates can be achieved by employing higher-order PAM and PS, enabled by low RIN of the QDLC line. In addition, the larger line spacing enables up to 80 GBd/λ transmission.

4. Conclusions

Increasing data transport capacity in campus DCI links has become necessary because of the widespread use of cloud-based applications and services. Due to the potential of photonic integration and wide wavelength tunability, the single-chip QDLC could be ideal for simple optical-domain reconfigurable wideband multi-channel systems. This work demonstrated aggregated data transmissions of 1.4 Tbps and 1 Tbps over 10 km SMF with 100 Gbps/λ PAM4 and PS-PAM8 signals by employing the QDLC source and reported a BER performance below the standard FEC limit. The device can potentially enable the next generation 800 GbE and 1.6 TbE energy-efficient links through photonic integration with suitable modulators and amplifiers for short-reach systems.

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