100 Gbps/λ Transmission with Quantum Dot O-Band Comb Source using 50 GBd PAM4/16QAM-OFDM Signals

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Abstract: We demonstrate a record high transmission rate of 100 Gbps/λ with 50 GBd PAM4 and 16QAM-OFDM signals using a packaged wavelength-tunable InAs/InGaAs quantum dot-based laser comb source for short-reach application. We successfully show the performance is within the standard FEC limits.

1. Introduction

The unceasing growth of data traffic, especially in short-reach systems with applications in data center interconnects (DCI) and passive optical networks (PON), demands considerable changes in the subsystem design. The use of advanced modulation formats operating at higher symbol rates coupled with parallel spectral channels can accommodate the growing demands in short-reach systems [1]. O-band systems present advantages compared with C-band systems since they offer lower inter-symbol interference due to ultra-low dispersion and are extremely robust against dispersion-induced power fading in high bandwidth systems. There are various options for generating parallel O-band channels, such as employing independent lasers or comb sources [3, 4]. The use of multiple tunable lasers is likely to increase the cost and the power requirements in the system [5]. Comb sources are multi-wavelength optical sources that allows dense photonic integration and can be more advantageous from a practical and economic perspective. Hence, O-band comb sources have great potential for future short-reach high-capacity systems [6]. A combination of fibre loss, split loss and switching loss can limit the performance of O-band short-reach systems based on comb sources for data center or access network applications, resulting in the need for O-band amplifiers [2]. Semiconductor optical amplifiers are favorable owing to their small foot print, reduced energy consumption, and most importantly their ability for photonic integration along with the laser source, modulators, filters, etc.

In this abstract, we present the experimental demonstration of the 100 Gbps/λ transmission of single carrier 50 GBd PAM4 and 50 GHz Hermitian symmetric 16QAM-OFDM signal over 10 km SMF using an Innolume InAs/InGaAs quantum dot-based laser comb (QDLC) and a SOA. The results that we present demonstrate the potential development of a compact small-form-factor module for high-capacity short-reach optical interconnects based on 1.3 μm multi-channel technology when employed with a silicon-integrated optical frequency comb modulator [7] and an SOA booster amplifier.

2. Device Characterization and Data Transmission

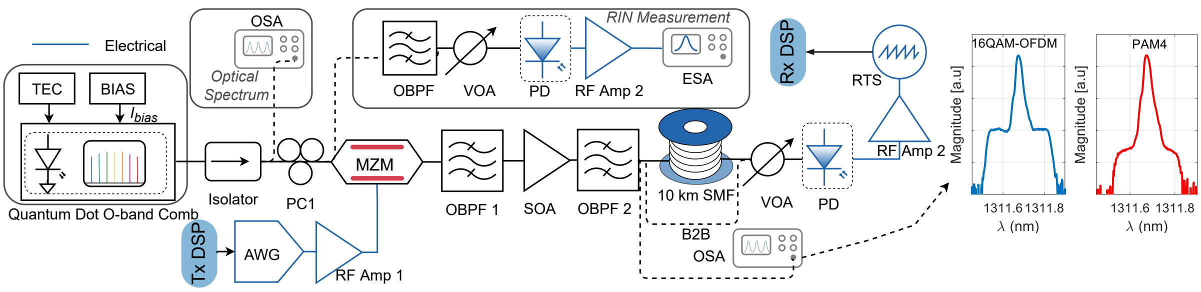
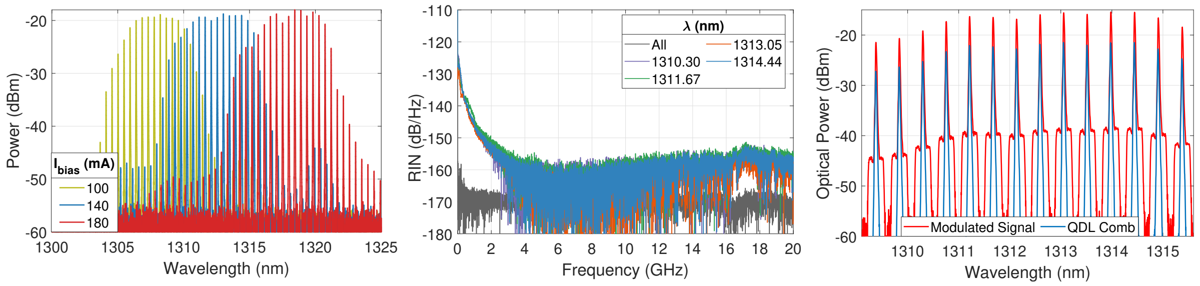


Fig. 1: Schematic of the experimental setup used for the measurement of RIN of the quantum dot O-band comb laser and transmission of 100 Gbps PAM4/16QAM OFDM (optical spectrum of modulated data shown in inset).

This O-band InAs/InGaAs quantum dot comb source is housed in a standard 14-pin butterfly package and has a total output power of around 25 mW with a power per line of $\sim$3 dBm for the central comb lines. We first characterise this comb source to determine its optical spectrum at different bias currents and the relative intensity noise (RIN) across the comb lines. The schematic of the experimental setup for the spectral and RIN characterisation of the optical lines, and the 100 Gbps signal transmission using the QDLC is shown in Fig. 1. We first operate the QDLC at different bias currents and Fig. 2 (a) shows the optical spectrum of the comb captured with a 0.01 *nm* resolution bandwidth optical spectrum analyser (OSA). For all the characterisation and transmission experiments, we control the temperature using an external temperature controller set to operate the QDLC at 24.5^{o}C. The longitudinal mode spacing of the QDLC is about 80 GHz, independent of the bias current value, and we show > 20 *nm* tunability in the wavelength of operation as the laser bias current is varied from 100 to 180 mA (the threshold current was 18 mA). We then perform the RIN characterisation of the QDLC lines at a bias current of 140 mA. We first filter out the line of interest using an O-band optical band pass filter (OBPF, EXFO XTM50) and then detect it using a 30 GHz bandwidth photodetector (PD). The detected signal is then amplified using a 50 GHz RF amplifier and is fed to the electrical spectrum analyser (ESA, RS FSW50). The electrical spectrum is then used to compute the RIN presented in Fig. 2 (b) for four comb lines across the spectrum.

The RIN of the entire comb source presents a level below -160 dB/Hz. When one line is filtered out the results in Fig. 2 (b) show additional RIN at low frequency due to mode partition noise, before the RIN falls to a value of below -150 dB/Hz after 2 GHz. We perform a system-level transmission demonstration with 50 GBd PAM4 and 50



(a) (b) (c)

Fig. 2: (a) Spectrum of longitudinal modes of the QDLC at various bias currents, (b) RIN spectrum of selected modes of QDLC for a bias current of 140 mA (C) Spectrum of the modulated QDLC with 100 Gbps PAM4 data.

GHz 16QAM-OFDM signal using a single comb line derived from QDLC. We generate the 50 GBd PAM4 signal offline as a part of transmitter-side digital signal processing (DSP). We apply raised cosine pulse shaping with 0.01 roll-off factor to reduce the electrical bandwidth to less than 26 GHz and load it in the arbitrary waveform generator (AWG), operating at 90 GS/s sampling rate. We generate the OFDM signals using a total of 256 sub-carriers with a sub-carrier spacing of 351.5 MHz. We use 70 data sub-carriers, each modulated with 16QAM symbols, for generating a Hermitian-symmetric real signal with 25 GHz electrical bandwidth. The generated real OFDM signal is loaded in the AWG, operating at 92 GS/s sampling rate. In both the PAM4 and OFDM cases, the total information rate is 100 Gbps.

A 40 GHz external modulator is used to modulate all the lines of the QDLC (biased at 140 mA) with the amplified 50 GBd PAM4 or 50 GHz real 16QAM-OFDM electrical signals. Figure 2 (c) shows the optical spectrum of the 14 modulated and unmodulated comb lines. We filter one of the modulated lines (at 1311.2 *nm*) using OBPF1 and amplify using a booster semiconductor optical amplifier (SOA), from -9 dBm to 11 dBm. The amplified signal was filtered to remove the out-of-band amplified spontaneous emission noise. The amplified modulated 100 Gbps signal is then transmitted in back-to-back (B2B) configuration and over 10 km standard single-mode fiber. To emulate a real system, we vary the signal power at the receiver (Prx) using a variable optical attenuator (VOA). The attenuated signal is then detected using a 30 GHz photodetector, amplified using 16 dB gain RF amplifier and digitized using a 33 GHz bandwidth real-time scope (RTS, 100 GS/s).

3. Transmission Results and Discussion

We process the captured signal using offline receiver-side DSP. In the case of the PAM4 signal, we employ a blind linear transversal feed-forward equaliser (FFE) with 151 (B2B)/201 (10 km) T-spaced taps. Here, we use a larger tap size to reduce the effect of component-induced ISI and the noise the SOA introduced. In the case of real OFDM signal, we estimate the channel response in the frequency domain using training symbols and use the estimated channel response to equalize the received signal using single-tap zero forcing frequency-domain equalizer (ZF-FDE). Figure 3 (a) shows the BER performance of the 50 GBd PAM4 signal, evaluated for B2B and 10 km SMF transmission scenarios. The BER performance attains the HD-FEC limit of 3.8×10^{-3} at -0.6 dBm and -0.3 dBm

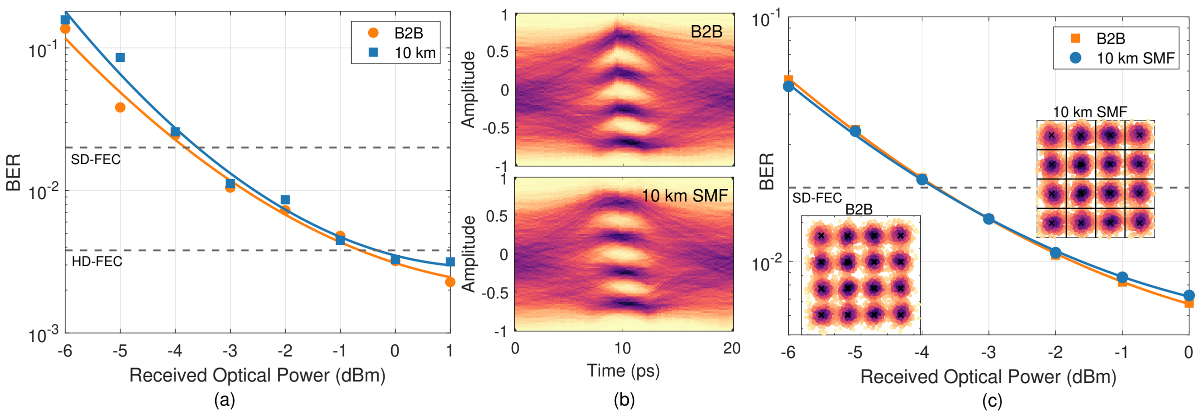


Fig. 3: (a) BER performance and (b) eye diagram (at 1 dBm Prx) of the processed 50 GBd PAM-4 signal. (c) BER performance of the 100 Gbps 16QAM-OFDM signal, with signal constellations evaluated at 0 dBm Prx (inset).

for B2B and 10 km SMF transmission, respectively. For both transmission scenarios, the BER performance attains the SD-FEC limit of 2.2×10^{-2} for Prx greater than -4 dBm. Figure 3 (b) shows the eye diagram of the processed 50 GBd PAM signal for B2B (top) and 10 km (bottom) cases, evaluated at 1 dBm Prx. The wide-opening of the eye diagrams in the two cases is a visual measure of the performance, indicating that error-free transmission can be achieved using forward error correction encoding with the appropriate overhead. Figure 3 (c) shows the BER performance for the 100 Gbps 16QAM-OFDM signal for various received power values. For both transmission scenarios, the BER performance of the OFDM signal attains an SD-FEC limit of 2.2×10^{-2} for Prx greater than -4 dBm, similar to the PAM signal transmission. The constellation diagrams of the offline processed signal are shown as an inset in Fig. 3 (c), evaluated at 0 dBm Prx.

The above results demonstrate the potential use of the QDLC for generating multiple wavelength channels for spectrally efficient data transmission in short-reach systems, such as in passive optical networks and data center interconnects. We have used FFE and ZF-FDE as a part of the receiver side DSP, however with advanced nonlinear and machine learning-based equalizers, the BER performance can be potentially improved by an order of magnitude [8]. In this demonstration, we have transmitted only one channel out of 14 channels (having flatness within 6 dB) for system demonstration purposes. By transmitting all the modulated lines from this QDLC, we can potentially achieve a total capacity of more than 1.4 Tbps spanning just over 6 nm bandwidth, even with a coarse grid spacing. It is also worth noting that for systems employing low bandwidth components ($< 10\ GHz$), the data rates can be achieved by employing PAM modulation with higher cadinality, and this device is very suitable for such applications thanks to its extremely low RIN.

4. Conclusion

Increasing data capacity per channel in short-reach systems, especially in data centres and PON applications, has become necessary. With the ability of photonic integration and wide wavelength tuning capability, the single chip InAs/GaAs quantum dot-based laser comb source could potentially be deployed for simple optical-domain reconfigurable wideband multi-channel systems. In this work we have demonstrated 100 Gbps/λ single carrier PAM4 and multi-carrier 16QAM-OFDM signal transmission over 10 km SMF employing the QD comb source, with performance being within the standard FEC limits. The device has the potential to enable $>$ Terabit/s energy efficient links through photonic integration with suitable modulators and amplifiers.

Acknowledgement

This work was supported in part by the Science Foundation Ireland under Grants 18/EPSRC/ 3591, 13/RC/2077-P2 and 12/RC/2276 P2 and in part by Graduate Short-Term Overseas Study Program in HUST.

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