100 Gbps PAM4 Transmissions over 50 km with 40 dB Power Budget for PON using a High-Gain Quantum Dot SOA

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Abstract: We experimentally demonstrate a 106 Gbps PON downstream signal transmission using a high-gain InAs/InGaAs quantum dot-based SOA as a preamplifier. We achieved a record-high power budget of 40 dB considering an HD-LDPC BER limit of 1×10^{-2}.

1. Introduction

The unceasing data traffic growth in broadband optical access networks demands considerable changes in the subsystem design to accommodate the requirements. Standardisation bodies such as IEEE and ITU-T have recommended 50 Gbps transmission in passive optical network (PON) systems [1,2]. The recommended 50G-PON is based on time division multiplexing (TDM) with a data rate of 50 Gbps downstream and time division multiple access (TDMA) with several data rates of 12.5 Gbps, 25 Gbps and 50 Gbps upstream. With constraints coming from the component's limited bandwidth and the chromatic dispersion from the fibre, solutions to achieve the required optical power budget (up to 29 dB) and sensitivity requirement in the high-speed PONs have interested the research community. In the 50G-PON, an integrated semiconductor optical amplifier (SOA) may be used to boost the optical signal at the optical line terminal (OLT) before transmission to accommodate for the high optical loss, and digital signal processing (DSP) can be employed at the optical network unit (ONU) to compensate for fibre transmission effects, and linear and nonlinear distortions from low-bandwidth components [3].

The latest amendment to the 50G-PON standard recommends using 4-level pulse amplitude modulation (PAM4) for the 50 Gbps links and extending to a single channel 100 Gbps access networks to support future capacity requirements. There have been various demonstrations of 100 Gbps PAM4 to achieve a power budget of 29 dB and beyond. In [4], the authors demonstrate a 29 dB power budget using a 13 GHz bandwidth direct modulation laser after 50 km transmission with SOA as a pre-amplifier. [5] demonstrates a 34 dB power budget with complex linear and nonlinear DSP at the transmitter and receiver in a 15 GHz bandlimited system. In [6], authors demonstrate a 29 dB power budget with a Mach Zender Modulator (MZM) and Praseodymium-doped fibre amplifier (PDFA) booster at the OLT and a SOA pre-amplified receiver after 20 km transmission. A real-time 100 Gbps transmission with a power budget of 34 dB after 40 km transmission at a hard-decision forward error correction (HD-FEC) bit error rate (BER) threshold of 1×10^{-2} (HD-LDPC limit) was reported in [7]. Operating the SOAs with a wider dynamic range is vital for PON systems; hence, using quantum dot SOAs over the quantum-well SOAs would be advantageous.

In this abstract, we present the experimental demonstration of a 106 Gbps PAM4 PON downstream transmission in O-band with over 40 dB power budget using a Innolume's high-gain quantum dot SOA preamplifier and offline DSP. We employ Nyquist shaping at the transmitter to make the 53 GBd PAM4 operate in a bandwidth-limited transmitter and demonstrate the performance with the linear and nonlinear equaliser at the receiver. At a pre-FEC BER of 1×10^{-2}, we achieve a power budget of 40 dB over 50 km fibre transmission. To the best of our knowledge, we present the first demonstration of 106 Gbps PAM4 PON system operating over up to 50 km transmission using a commercial O-band quantum dot SOA without deploying any amplifier at the OLT.

2. Device Characterisation and Data Transmission

The schematic of the experimental setup for characterising the quantum dot SOA (QD-SOA) and the 53 GBd PAM4 downstream transmission is shown in Fig. 1. The O-band InAs/InGaAs quantum dot SOA is housed in a standard 14-pin butterfly package and is controlled using a laser driver and temperature controller. We first characterise this QD-SOA at different input powers and operate at two different bias currents. We operate the QD-SOA at 27^{o}C for all the characterisation and transmission experiments. We employ a distributed feedback (DFB) laser operated at 1304.8 nm as the source of the characterisation and transmission. We first vary the input power into the QD-SOA using a variable optical attenuator (VOA 1) and observe the gain and the output power obtained, as shown in Fig. 2 (a), by operating the QD-SOA at 500 mA and 1000 mA bias currents. We observe that the gain decreases as the input power increases, and the maximum overall gain achieved at -28 dBm input power is about 31 dB and 38.4 dB at 500 mA and 1000 mA, respectively. Such a high gain enables a large optical power budget in the PON systems. We observe the 3 dB compression point (P_{3dB}) at an input power of -8 dBm for a bias current of 1A. However, the gain curve does become nonlinear after input powers of about -20 dBm. With an input power level less than -20 dBm, the signals will mainly be affected by the SOA's amplified spontaneous emission (ASE) noise and as the signal power increases beyond -20 dBm the signals will become increasingly more distorted by the saturation effect from the QD-SOA. Figure 2 (b) shows the ASE noise spectrum of the SOA operated at 500 mA and 1000 mA, demonstrating a 3 dB bandwidth of about 17 and 20 nm, respectively. The peaks at 1300 nm and 1200 nm for the 1000 mA bias case correspond to the emission from the QD's ground and excited states, respectively.

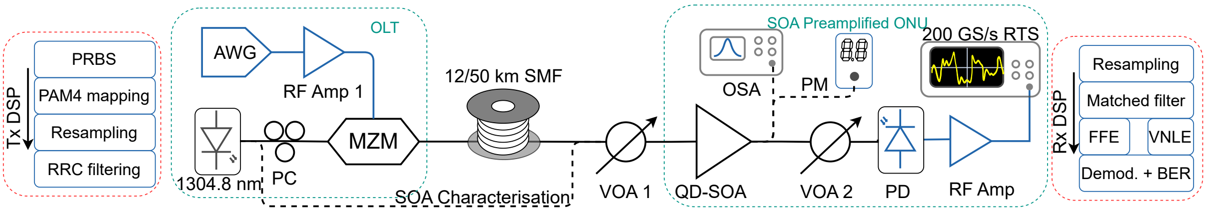

Fig. 1: Schematic of the experimental setup for characterising the QD-SOA and transmitting 53 GBd PAM4 PON signal.

Figure 2 (c) shows the normalised optical spectrum of the modulated line and the amplified line captured with a 0.01 nm resolution bandwidth optical spectrum analyser (OSA). We can observe that even with the addition of the SOA, the optical signal-to-noise ratio (OSNR) is still around 40 dB. We also perform the relative intensity noise (RIN) characterisation of the laser source as shown in the inset of Fig. 2 (c), presenting a level below -155 dB/Hz, indicating the capability to perform higher cardinality PAM. We then demonstrate a system-level PON

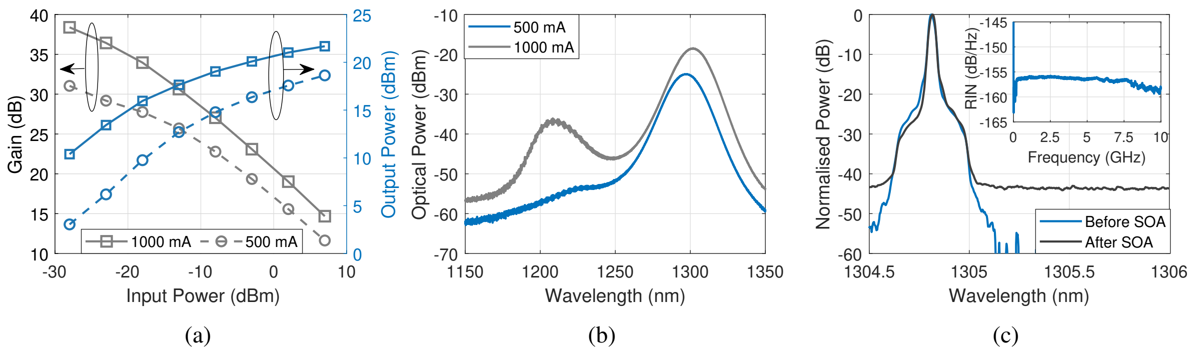

Fig. 2: (a) QD-SOA overall gain and output power versus input power, (b) Spectrum of ASE noise at various bias currents (c) Attenuated spectrum of the modulated 106 Gbps PAM4 PON signal before and after QD-SOA (inset:RIN of the laser).

transmission with 53 GBd PAM4 signal over different fibre lengths. We generate the 53 GBd PAM4 signal offline as a part of transmitter-side digital signal processing (DSP). We apply root-raised cosine (RRC) pulse shaping with a 0.1 roll-off factor to reduce the electrical bandwidth to less than 30 GHz and load it in the arbitrary waveform generator (AWG), operating at 92.75 GS/s sampling rate. A 30 GHz external modulator modulates the optical carrier at 1304.8 nm with the amplified (using RF Amp 1) 53 GBd PAM4 electrical signals. The modulated downstream 106 Gbps signal is transmitted in a back-to-back (B2B) configuration and over 12/50 km standard single-mode fibre with a launch power of -0.5 dBm. We do not employ any OLT side amplifier before transmission. The transmitted signal is amplified using the QD-SOA set at the appropriate bias current. To emulate a real system, we vary the signal power at the receiver (Prx) using VOA 2. The attenuated signal is then detected using a 70 GHz photodetector, amplified using a 16 dB gain RF amplifier and digitized using a 70 GHz bandwidth real-time scope (RTS, 200 GS/s). The system is operated within an overall bandwidth of 30 GHz, determined primarily by the limited bandwidth of the AWG and MZM.

3. Transmission Results and Discussion

We first study the BER performance of the signal when amplified using the QD-SOA at different input power levels. We evaluate the performance at a fixed optical power of 0 dBm on the photodiode. We process the captured

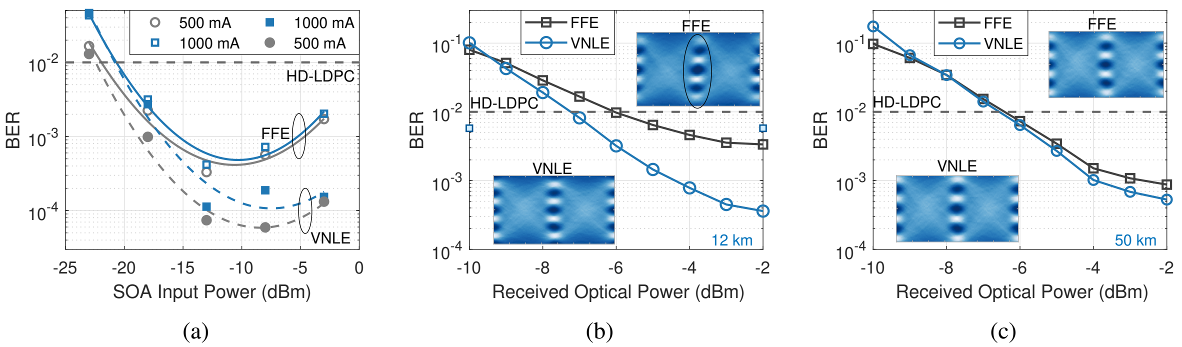

Fig. 3: (a) BER as a function of input power into QD-SOA in B2B transmission, BER as a function of received optical power after (b) 12 km and (C) 50 km transmission.

signal using offline receiver-side DSP. The received signal is first resampled and matched filtered using the RRC prototype filter. We employ a linear transversal feed-forward equaliser (FFE) with 31 T-spaced taps and also evaluate the performance with a second-order Volterra nonlinear equaliser (VNLE) with 31 linear and 25 nonlinear taps with a beating of 5 neighbours [8]. We then demodulate and measure the BER performance. Figure 3 (a) shows the BER performance with FFE and VNLE equalisers versus the input power into the QD-SOA at two different bias currents without any fibre transmission. We observe a significant BER performance improvement with VNLE compared to FFE as the input power exceeds -10 dBm due to its ability to correct the nonlinear distortion due to SOA saturation. With both equalisers, the performance reached the HD-LDPC at a Prx of -22 and -21 dBm at 500 and 1000 mA, respectively. We operate the QD-SOA at 1000 mA bias current for the fibre transmission cases. Figure 3 (b) shows the BER performance of the PON signal as a function of Prx after 12 km fibre transmission. In this case, the power input to the QD-SOA was -6 dBm ($\gg P_{3dB}$) after transmission; hence, VNLE has an improved BER performance compared to FFE. The BER performance attains the HD-LDPC limit at -6 dBm and -7 dBm for FFE and VNLE equalisers, respectively. Figure 3 (c) shows the BER performance of the PON signal as a function of Prx after 50 km fibre transmission. In this case, the power input to the QD-SOA was -18 dBm after transmission; hence, VNLE and FFE performance is comparable, albeit for a slight improvement with the VNLE, as the SOA is still in the early saturation regime. In both cases, the BER performance attains the HD-LDPC limit for Prx greater than -6.5 dBm. For both transmission scenarios, the eye diagrams of the processed signal at -3 dBm Prx are shown as an inset in Fig. 3 (b) & (c). We can observe the effect of SOA nonlinearity in the eye diagram after processing with FFE in the 12 km case and how VNLE is correcting it. Considering the HD-LDPC FEC limit with a transmit power of -0.5 dBm, QD-SOA gain of 34 dB (for an input power of -18 dBm) and a receiver sensitivity of -6.5 dBm, we achieve a 40 dB power budget after 50 km fibre transmission. The above results demonstrate the potential use of the high-gain QD-SOA in legacy and future high-speed downstream PON systems operating up to 50 km. The ability of the QD-SOA to operate below the FEC limit for a wide range of input powers can be beneficial in PON systems, where the signals arrive at different power levels at different ONUs. The inclusion of a booster amplifier in the OLT, as in the 50G-PON scenario, with a transmit power of 10 dBm over a 12 km fibre, would enable a system that can support 256 users, each employing the SOA preamplified receiver.

4. Conclusion

In this work, we have demonstrated 106 Gbps PAM4 PON transmission using a 30 GHz MZM in the O-band assisted by the high-gain QD-SOA and receiver side DSP to achieve a 40 dB power budget. The results demonstrate that the QD-SOA can support 12 km (regular PON) and 50 km (long reach PON) fibre transmissions with an HD-LDPC FEC. The device can potentially enable high-capacity links for 256 users simultaneously through photonic integration with suitable photodetectors.

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