Bidirectional 100G/150G Amplified Transmission With a QD-SOA for Future Passive Optical Networks

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***Abstract*—This work investigates optically amplified bidirectional transmission with a quantum-dot semiconductor optical amplifier for next-generation 100G passive optical networks. We experimentally demonstrate 100/150 Gbit/s uplink/downlink bidirectional PAM-4 transmissions employing a quantum-dot semiconductor optical amplifier in the remote node of an optical access network. After 20 km optically amplified transmission, we attain the uplink/downlink power budgets of 32.3 dB/29 dB at the HD-LDPC bit error ratio decision threshold of 10^{-2} with an overhead of 15.5%, satisfying the power budget requirements of a legacy passive optical network with net (gross) achievable uplink/downlink data rates of 84.4/126.7 (100/150) Gbit/s, respectively.**

***Index Terms*—Intensity modulation and direct detection, Mach-Zehnder modulator, pulse amplitude modulation, passive optical networks, quantum-dot, semiconductor optical amplifier, bidirectional transmission.**

I. Introduction

THE evolution of emerging technology and services, such as 4K/8K video, artificial intelligence (AI), Internet-of-Things (IoT), etc., resulted in an unprecedented capacity demand in optical access networks. The latest generation of the passive optical network (PON) standard, called 50G PON [1], supports 50 Gbit/s uplink/downlink (UL/DL) data over a single wavelength in the O-band using a time-division multiplexing (TDM) technique and non-return-to-zero (NRZ) modulation format. For the next-generation PON standards, 100G PON could be one of the possible solutions [2], [3] and is now at the research level [4], [5], [6], [7], [8], [9]. The 100G PON will probably be O-band based and may utilize a four-level pulse amplitude modulation (PAM-4) format, more advanced digital signal processing (DSP), and TDM techniques, as wavelength management is usually complex and costly for PONs [3]. However, due to the insertion of a passive splitter to serve multiple users, a typical TDM-PON incurs a significant splitting loss.

Previous works on intensity modulation and direct detection (IM/DD) PON with extended capacity and power budgets utilized higher output power directly modulated lasers (DMLs) [4], [5], higher-sensitivity avalanche photodetectors (APDs) [6], costly praseodymium-doped fiber amplifiers (PDFA) [7], Raman amplifiers [5], or semiconductor optical amplifiers (SOAs) based on quantum-well (QW) and quantum-dot (QD) technologies [8], [9], [10]. For provisioning 100G-class PON or beyond, the DMLs and APDs may not be suitable due to a lack of required bandwidths and laser chirp; therefore, monolithically integrated laser and electro-absorption modulator (EAM)-based transmitters [6] and PIN-based receivers with limited sensitivity are the ultimate choice. Although an integrated SOA-PIN receiver could be another option [6], the cost and power consumption of the optical network terminal (ONT) and overall PON could grow n times to support n ONTs in the network. To meet the loss budget requirements of PON, SOAs based on QD materials have gained interest recently due to their fast gain recovery time, higher saturation output power, and inhomogeneous gain broadening, leading to patterning-free amplifications and reduced nonlinear penalties caused by cross-gain modulation (XGM) in amplified WDM systems [9], [10], [11]. Bidirectional (BiDi) amplification with an SOA can be a promising solution for cost- and energy-efficient optical access networks. BiDi SOA-amplified PON was targeted for NG-PON2 running at 10G [12]. The recent demonstration of a QD-SOA-operated BiDi 100G system work does not investigate the BiDi data transmission performance [13].

In this letter, we experimentally demonstrate optically amplified BiDi PAM-4 transmissions in the O-band for next-generation optical access networks, supporting total data rates of 100 Gbit/s in the UL and 150 Gbit/s in the DL. Dedicated wavelengths are utilized in the system for the UL and DL transmissions. XGM is one of the major issues for the BiDi amplification of signals at different wavelengths, as is the case in PON systems. We demonstrate that by placing a single high-gain QD-SOA in the remote node (RN), it is possible to concurrently amplify the UL and DL signals that could provision n ONTs in the network without increasing the cost and power consumption of the PON for each provisioned ONT.

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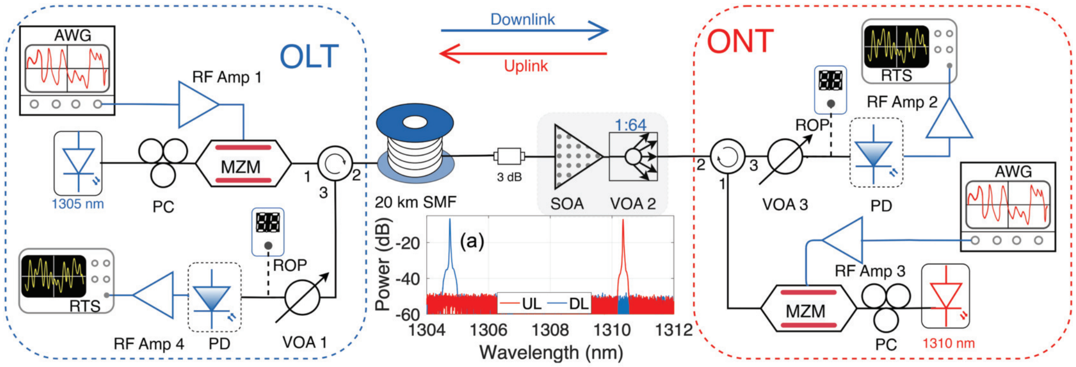

Fig. 1. Experimental setup for QD-SOA amplified 100G/150G BiDi PAM-4 transmission. (a) Modulated UL and DL PAM-4 data.

However, such a PON design can be named ‘q-PON’ or ‘quasi-PON’ as it would require provisioning electric power in the RN, which could be provided through a long-life battery or by installing cabinets with power distribution modules and power socket facilities. The key advantage of moving to this q-PON architecture, with power supplied to the remote node, would be the ability to extend the reach and/or the number of users served from a single PON. After continuous-mode BiDi transmissions over a 20 km single-mode fiber (SMF), the UL and DL optical power budgets of 32.3 dB and 29 dB are achieved with a T-spaced 31-tap feed-forward equalizer (FFE), respectively, at the bit error ratio (BER) decision threshold of 10^{-2}. Despite continuous mode traffic in the UL, the results presented in this work are important, as they validate the effectiveness of a QD-SOA in reducing several nonlinear SOA impairments, such as XGM, pattering effects, and gain saturation, during simultaneous amplification of BiDi data in the RN of a PON.

II. Experimental Setup

The experimental setup is illustrated in Fig. 1. To boost the power budget, the UL and DL continuous-mode signals are amplified by employing a single BiDi QD-SOA placed in the RN or local exchange of an optical access network. In previous works, it is observed that optically amplified RN could potentially mitigate the passive losses in the network and increase the PON power budget [10], [14], [15], [16]. The distributed feedback (DFB) lasers emitting at 1310 nm and 1304.9 nm with optical output powers of about 14 dBm and 10 dBm are utilized as light sources in the experiment for the UL and DL transmissions, respectively. A pair of single-ended Mach-Zehnder modulators (MZMs) with 3-dB optical bandwidths of about 45 GHz and 30 GHz are employed at the OLT- (optical line terminal) and ONT-side to modulate electrical PAM-4 signals onto the optical carriers, respectively. As the ONT is more cost-sensitive compared with an OLT, we demonstrate a high-speed PON with asymmetric line rates, in which the ONT transmitter is equipped with slightly lower bandwidth optical and RF components due to the increased cost of high-bandwidth components. Both MZMs are biased at the quadrature point by applying DC voltages. For the generation of UL and DL signals, the digital PAM-4 signals are generated offline in MATLAB with a sequence length of 2^{16}, which are upsampled 4.5 and 3 times, respectively, pulse-shaped using a root-raised cosine (RRC) filter with a roll-off factor of 0.1, and pre-distorted using *arcsin* function to reduce the impact of MZM-induced nonlinearity. To drive the MZMs, two independent PAM-4 data streams are loaded to a two-channel arbitrary waveform generator (AWG) with 70 GHz analog bandwidth running at 225 GSa/s to generate 50 GBaud and 75 GBaud PAM-4 signals with a peak-to-peak voltage (Vpp) of 300 mV for the UL and DL transmissions. The UL and DL electrical data are boosted by RF amplifiers with gains of 23 dB and 22 dB, and 3-dB bandwidths of 55 GHz and 66 GHz, respectively. Upon modulation, the average optical output powers from the ONT and OLT transmitters are about 7.3 dBm and 2.4 dBm (measured at port-2 of the OLT-side circulator), respectively. The normalized modulated spectrum with 50 GBaud and 75 Gbaud PAM-4 data is presented in Fig. 1(a). In the figure, the modulated UL and DL data are denoted with red and blue colors, respectively. In the DL, the optical signals are transmitted over a 20 km feeder fiber with an attenuation coefficient of 0.35 dB/km, followed by a QD-SOA to compensate for the transmissions and splitter losses in the network and to satisfy the power budget requirements of 29 dB for a legacy PON. Next, with the help of a variable optical attenuator (VOA), the SOA-amplified optical signals are attenuated by 18 dB to emulate 1:64 passive splitter loss in the network. The UL signals traverse in the opposite direction. Two three-port optical circulators are placed at each end of a feeder fiber to serve add-and-drop functionalities for BiDi transmission in the network.

The incoming UL/DL signals from port 2 to port 3 of optical circulators are directly detected using a 70 GHz PD. A VOA is placed before the PD to adjust the received optical power (ROP). Unless stated otherwise, the ROP is always measured at the input of the PD during the experiment, as shown in Fig. 1. Upon detection, the electrical PAM-4 signals are amplified using a 22 dB gain RF amplifier. The RF amplifier provides a 3-dB bandwidth of 66 GHz. The amplified PAM-4 signals are captured for offline MATLAB processing using a 70 GHz real-time scope (RTS), which operates at 256 GSa/s. The OLT/ONT receiver-side offline DSP includes RRC matched-filtering, resampling, symbol time synchronization, and symbol equalizations with a T-spaced 31-tap FFE (optimized by comparing BER versus FFE taps) to remove the signal distortions due to bandwidth limitations. Finally, the recovered PAM-4 symbols are demodulated to measure the BER performance through error counting.

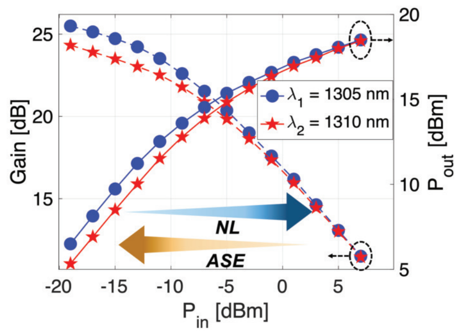

Fig. 2. SOA gain and output power versus SOA input power.

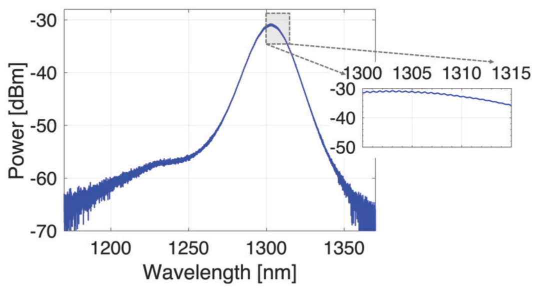

Fig. 3. ASE spectrum of the SOA.

III. Experimental Results

In Figs. 2–4, we investigate the characteristics and performance of the QD-SOA. In the experiment, the SOA bias current and temperature are set to 500 mA and 35°C, respectively. The measured α-factor of the QD-SOA is around one, and indeed, a key advantage of quantum dot devices for use in optical systems is their low α-factor. The employed QD-SOA is polarization sensitive with a polarization extinction ratio (PER) of 18 dB, which would be an issue for practical implementation. The development of polarization-insensitive SOA is required, and there has been substantial work in this direction [17]. One way to attain polarization insensitivity for an inline QD-SOA is by introducing polarization diversity, although this would increase cost and impact the gain [18].

Fig. 2 shows the SOA gains and output power for the two operating wavelengths of 1305 nm and 1310 nm as a function of the SOA input power. We can observe that the SOA gain is wavelength-dependent. With an increasing P_{in}, the SOA exhibits significant nonlinearity due to gain saturation, which can dictate the overall system performance. As the P_{in} decreases, the SOA moves towards the linear operating condition. However, amplified spontaneous emission (ASE) noise generated by the SOA can affect the overall system performance at lower input powers.

The gain spectrum of the QD-SOA is presented in Fig. 3. It can be seen that the SOA provides a 3-dB gain bandwidth of about 20 nm. Even though the gain peak of the SOA is located at 1303 nm, the SOA still provides a high gain response with reasonable flatness in the operating wavelength region of 1305-1310 nm. The gain peak of the SOA can be shifted towards the longer wavelength by setting a higher operating temperature, which would impact the SOA gain. It is worth mentioning that a 5 nm of narrow wavelength spacing is chosen between the UL and DL wavelength bands due to a 20 nm limited bandwidth of the QD-SOA. The development of 50 nm or wider bandwidth QD-SOAs is currently at the research level [13], and this should enable the operation of the system presented in this work with larger channel spacing between UL and DL, as anticipated for practical implementations.

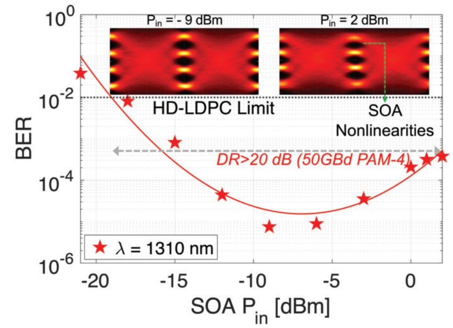

Fig. 4. BERs of 50 GBaud UL PAM-4 signals versus SOA input power in BtB single wavelength amplification.

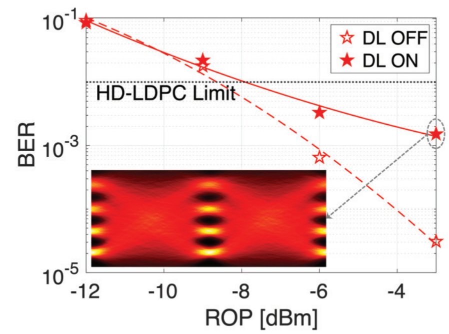

Fig. 5. BER versus ROP after 50 GBaud optically amplified UL PAM-4 data transmissions over 20 km.

In Fig. 4, we plot the BERs of 50 GBaud UL PAM-4 signals after unidirectional (UniDi) transmission versus SOA input power. The measured dynamic range (DR) of the QD-SOA is >20 dB at a BER threshold of 10^{-2}, which justifies the device's suitability for amplifying bursty UL data with varying levels of attenuation before arriving at the RN. The BER shows that when the SOA input power is above/below −9 dBm, the performance deteriorates due to increased SOA nonlinearities/ASE noise. The eye diagrams in Fig. 4 at different input powers to the SOA clearly show the eye distortion due to gain saturation at the higher input power.

In Figs. 5 and 6, we plot the BER results for the UL and DL signals as a function of ROP after UniDi and BiDi amplified transmissions over a 20 km SMF, respectively. The dashed and solid lines show the BER results for UniDi and BiDi transmissions, respectively. It is worth mentioning that for UniDi UL and UniDi DL signal transmissions, the other laser is kept OFF, and the SOA amplifies the signal coming only from one direction. For BiDi transmission, both lasers are ON during the experiment. In the experiment, as presented in Fig. 1, a 3-dB attenuator is placed before the SOA to reduce the SOA input power for the DL signal and attenuate the SOA-amplified UL signals. We find that the role of the 3-dB attenuator during BiDi transmission is critical to minimize SOA-induced gain saturation for the DL signal and fiber nonlinear penalties such as stimulated Brillouin scattering (SBS) from the UL signal. We note that the input signal powers into the SOA are

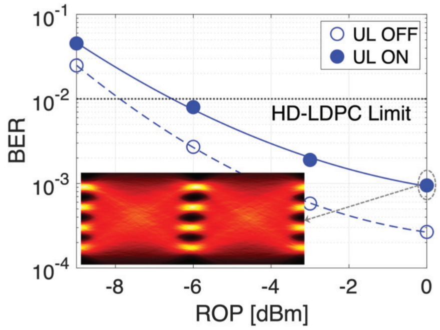

Fig. 6. BER as a function of ROP after 75 GBaud QD-SOA amplified DL PAM-4 data transmissions over 20 km of an SMF.

−10.7 dBm and −9.2 dBm in the UL and DL directions, respectively. After UniDi and BiDi transmissions, both UL and DL signals can reach the target hard-decision low-density parity-check (HD-LDPC) BER decision threshold of 10^{-2}, as defined in ITU-T G.9804.3 that adapts LDPC (17280,14592) with a code rate of 0.844 (overhead 15.5%) for error corrections [1]. As expected, the UniDi transmission system performs better than the BiDi for both UL and DL. The UniDi UL and DL signals show gains of about 0.6 dB and 1.35 dB, respectively, at the BER threshold of 10^{-2} compared with the BiDi SOA-amplified link. With amplified BiDi transmission, the total input signal power into the SOA increases when both lasers are ON, leading to some SOA-induced gain saturation and XGM penalties. After accounting for circulator insertion loss of about 1.3 dB, the 3-dB attenuator, 1:64 splits, and the SOA UL/DL output powers (gains) of around 11.5/13.4 dBm (22.2/22.6 dB), the experimental results report optical power budgets of 32.3 dB and 29 dB after QD-SOA amplified BiDi transmissions with gross data rates of 100 Gbit/s and 150 Gbit/s over a 20 km SMF for the UL and DL, respectively. After subtracting the FEC overhead, the net data achievable rates are about 84.4 and 126.7 Gbit/s for the UL and DL, respectively. The total power budget of the SOA-amplified PON is calculated considering the SOA gain and is obtained by adding the feeder and access budgets at the HD-LDPC BER limit threshold of 10^{-2}. In the DL direction, the feeder and access budgets can be defined as the allowable loss (to ensure received BER is at the HD-LDPC BER limit) of optical power from OLT to the RN (before SOA) and from RN (after SOA) to the ONT, respectively. In the insets of Figs. 5 and 6, the equalized PAM-4 eye diagrams for 50 GBaud UL and 75 GBaud DL data are shown after BiDi transmissions at ROPs of −3 and 0 dBm, respectively. A little skew is observed in the 75 GBaud PAM-4 eye diagram due to the interplay with the SOA nonlinear chirp and residual dispersion at 1305 nm.

IV. Conclusion

We report 100 Gbit/s UL and 150 Gbit/s DL PAM-4 transmissions over 20 km for access networks. With a BiDi QD-SOA amplified feeder link, UL and DL optical power budgets of 32.3 dB and 29 dB are achieved, respectively, satisfying the 29 dB link budget requirements for access networks. The results presented in this letter illustrate the benefits of employing a QD-SOA in an amplified BiDi PON, as it shows tolerance against various SOA nonlinearities. This work only considers continuous-mode UL traffic, whereas, in reality, the UL traffic is bursty in nature, which may further affect system performance with a shared SOA for UL and DL. Given the wide DR and limited XGM we have observed in the QD SOAs to date, we still consider the device suitable for practical BiDi transmission in an amplified PON, and the performance of simultaneously amplifying the continuous DL and bursty UL data with the QD-SOA will be a subject for future study.

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