Performance comparison of QD-SOA, QW-SOA, Bulk-SOA and PDFA for multi-Tbps O-band WDM links

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Abstract: We experimentally compare QD-SOA to QW-SOA, bulk-SOA, and PDFA for coherent and IM/DD in the O-band at 10 km. A 1.152 Tbps/λ WDM coherent transmission is achieved with the QD-SOA.

1. Introduction

To address the growing demand for short-reach intra-datacenter and inter-datacenter capacity, coherent transceivers with higher sensitivity and wavelength division multiplexing (WDM) are being considered as key candidates to increase the overall capacity and reach [1, 2]. The distance and receiving sensitivity of O-band transmissions are limited by higher optical fiber attenuation factor, while WDM systems introduce more passive losses such as multiplexers. Using optical amplifiers in the O-band allows for longer reach and enables high channel count configurations to be deployable [3]. However, in the O-band, the choice of amplifying technology is still unclear, especially within the coherent transmission realm. Semiconductor optical amplifiers (SOA) are already being explored for intensity modulation and direct detection (IM/DD) systems as a way to provide enough signal power at the receiver end [4]. However, bulk SOAs are known to exhibit a high noise figure and produce non-linear distortion, which discourages their use for optical signal amplification. Additionally, SOAs normally induce signal chirp, which degrades coherent signals even more. Advancements in quantum-dot (QD) technology allow for QD-SOAs to produce much lower distortion and chirp as compared to their quantum-well (QW) and bulk counterparts [5]. This is important because SOAs are a good candidate for the O-band datacenter-interconnects space because of their small footprint, smaller power consumption than praseodymium-doped fiber amplifiers (PDFA), and most importantly their ability to be integrated into a photonic integrated circuit (PIC).

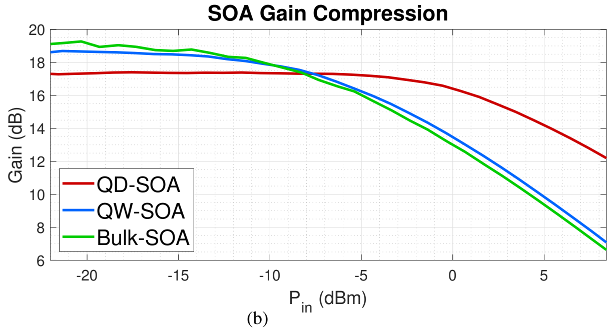
Notwithstanding, the overall performance and nonlinear gain dynamics offered by the different SOA technologies have yet to be tested and compared among them and against fiber amplifiers for both IM/DD and coherent modulation at the high baud rates needed to set up the next generation of PICs. This empirical study is important to simplify the amplifier choice given a certain system topology (modulation format, baud rates, etc.). Therefore, in this contribution, we first present a comparison of QD, QW, and bulk SOAs by considering two key performance parameters that affect waveform amplitude and phase, namely, gain recovery time (GRT) and linewidth enhancement factor (Henry or α-factor). Next and importantly, we extend our analysis to the high-speed system arena in the O-band by investigating the BER performance of IM/DD and coherent systems that rely on this kind of amplifier and the PDFA. We experimentally demonstrate in section 3 that the QD-SOA outperforms the PDFA and other SOAs in both coherent and IM/DD at high baud rates and is capable of amplifying multi-Tbps WDM systems.

2. SOA Characterization

In this section, we compare some relevant characteristics we measured in bulk and QW-SOAs (InPhenix IP-SAD1301) having similar attributes, as well as in a QD-SOA from Innolume. The main results are summarized in Fig. 1 a). They are complemented with "typical" values derived from the literature. A fair comparison requires operating all the SOAs out of saturation. Otherwise, lower saturation power SOAs would suffer from added non-linear distortion. Fig. 1 b) depicts this parameter measured as a function of (CW) input power into the SOA. The corresponding saturation powers are presented in Fig. 1 a) (first column). The QD-SOA exhibits a higher input saturation power (3dB gain reduction), P_{in}^{sat}. All SOAs are biased at their maximal gain point. Measurement of the α-factor is important in connection to chirp-induced pulse broadening in IM/DD systems and unwanted phase-modulation-induced constellation distortion in coherent systems. This parameter of the SOA relates, in a simple manner, the change of the active layer refractive index to the change of the material gain in response to carrier density variations. Hence, a low value of the α-factor is desirable for transmission applications. Column 3 of Fig. 1 a) shows the measured α-factor for all SOAs. Apart from the bulk SOA, which is showing a lower than predicted α-factor, they fall within the expected range, as reported in Column 2 (from the literature). The QD-SOA exhibits

SOA Type	P_{in}^{sat} (dBm)	α-factor (literature)	α-factor (measured)	GRT (literature)	GRT (measured)
QD	4.76	0.1-2.4 [6]	0.6-1.2	100s fs - 10s ps [7]	115.4 ps
QW	-3.66	2.4-3 [8]	2.7-3.2	100s ps [6]	238.9 ps
Bulk	-5.19	4-8 [9]	3.2-4.0	>100 ps [6]	239.3 ps

(a)



(b)

Fig. 1: a) Saturation power, α-factor and gain recovery times (GRT) b) Gain compression curves for all SOA types

the lowest value and, hence, the best performance, as confirmed in the transmission experiments. The dynamics of the carrier density are determined by the SOA recovery time. Measured values for all SOAs using a pump-probe technique are presented in column 5 of Fig. 1 a). Since this parameter value is very dependent on operating characteristics of the SOA, it is always difficult to be matched with the figures reported in the literature. In spite of this, the fastest device is the QD-SOA. This generally translates into better performance in high-speed transmission systems compared to the QW and bulk SOAs, which exhibit a similar carrier density response. For instance, a fast SOA leads to data-patterning-free amplification when operated close to saturation, resulting in a greater amplifier dynamic range. This is a desirable characteristic, especially when the active device is operated as a booster.

3. Transmission experiment setup and system performance results

Fig. 2 shows the experimental setup and DSP stack employed for both the coherent (a) and IM/DD (b) experiments. For the former setup, we first generate 2^{19} symbols by Mersenne Twister. The symbols are then root-raised cosine pulse-shaped at 2 samples per symbol (sps) and resampled to match the AWG's sampling rate (256 GSa/s). A pre-emphasis filter is applied to the signal to compensate for the RF connections and AWG frequency response. The RF signal is then fed to the thin-film lithium niobate (TFLN) IQ modulator (IQM) with a 70GHz GSG-GSG RF probe. The single polarization TFLN IQM has a V_π of 1.7V at low MHz frequencies. As shown in the figure, four channels derived from 16dBm DFB lasers are multiplexed and bulk-modulated by the TFLN IQM. The optical power into the amplifier is -12 dBm (combined power of all four channels). All four amplifiers are interchanged, and the experiment is repeated for each amplifier. The PDFA used has a noise figure of 6.5dB and its gain is adjusted to match the gain of the SOAs. Because the gain across all three SOAs at that optical input power is similar (17-18 dB), the received optical power (ROP) is not adjusted. The signal is then fed to a dual polarization emulator [2]. The dual polarization signal then travels along 10 km of SSMF fiber. The channel of interest is selected with the local oscillator and fed into a 2x8 dual polarization hybrid and converted into an electrical signal by four 70GHz balanced photodiodes (BPD). The electrical signal is then sampled by a 100GHz bandwidth 256 GSa/s 4-channel RTO. The LO fed to the hybrid is a 16dBm DFB laser tuned to the channel of interest. The receiver DSP is done offline. The sampled signal is first deskewed and resampled to 2 sps. The LO frequency offset is compensated. The samples are synchronized and match-filtered. Finally, a 4x4 multiple input multiple output (MIMO) equalizer with real coefficients interleaved with a first-order phase-lock loop (PLL) is used to compensate for linear distortion and phase noise as well as the IQM frequency response. The recovered symbols are unmapped into bits and the BER is evaluated by bit counting. The IM/DD setup operates in the same way except for the DSP routine. The dual-polarization emulator, the 2x8 hybrid, and the LO are removed and VOA1 is added to normalize the ROP. The input optical power into the amplifier is -6dBm (combined power of all four channels). At the transmitter side, 2^{19} PAM symbols are generated by Mersenne Twister. At the receiver side, the signal is resampled to 2 sps and synchronized. To compensate for the linear distortion, a feed-forward equalizer is used. Finally, the received symbols are unmapped to a binary sequence and compared to the transmitted sequence

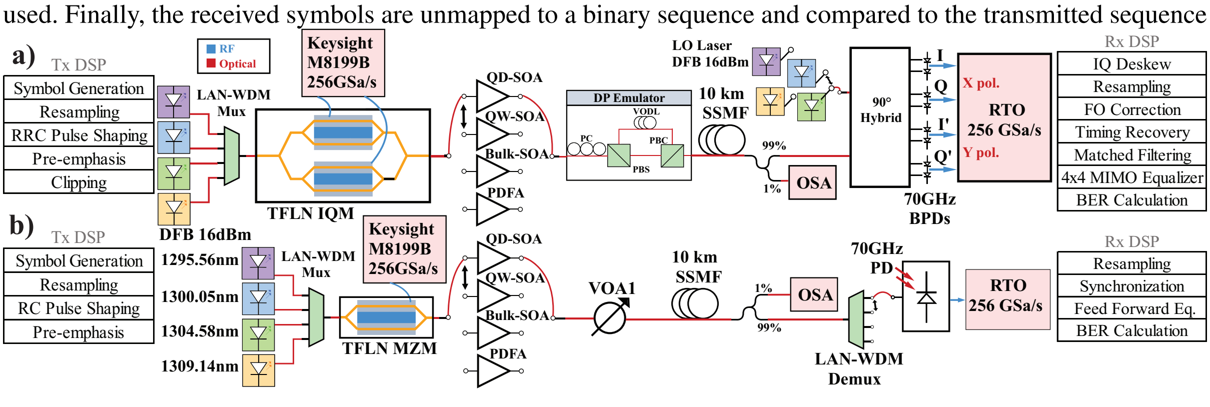


Fig. 2: a) Experimental setup and DSP stacks used for the coherent experiment. b) Experimental setup and DSP stacks used for the IM/DD experiment.

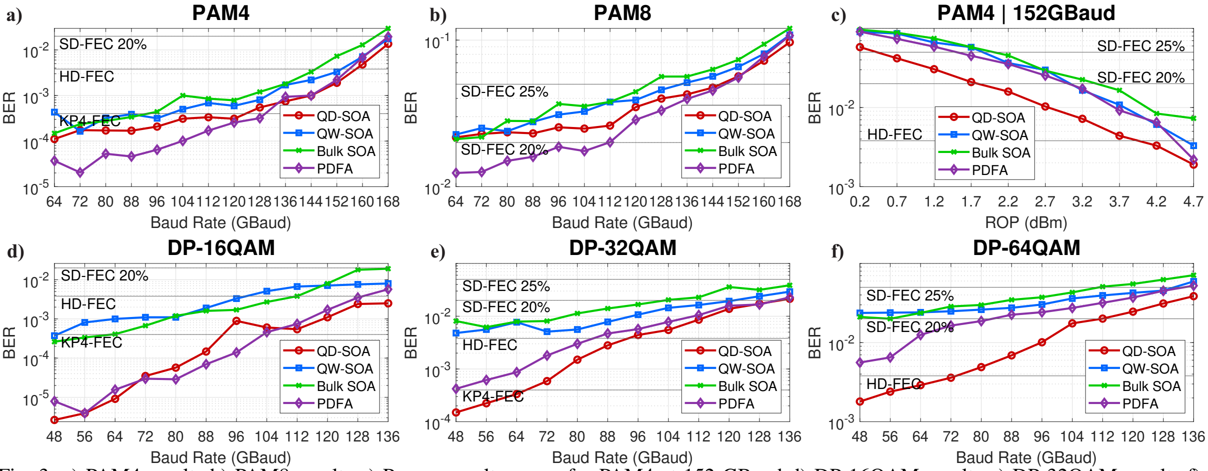


Fig. 3: a) PAM4 results b) PAM8 results c) Power penalty curve for PAM4 at 152 GBaud d) DP-16QAM results e) DP-32QAM results f) DP-64QAM results.

to calculate the BER. Although four channels are being transmitted at once, only the 1304.58 nm wavelength is being measured and reported for both the coherent and IM/DD experiments. Given the DSP stacks used and the large gain spectrum of the SOAs ($>$ 30 nm), we don't expect these results to differ from channel to channel. The amplifier comparison results for both IM/DD and coherent are summarized in Fig. 3. The PAM4 results show a successful net transmission of 268.8 Gbps under the 20% OH SD-FEC threshold for all amplifiers except the bulk SOA. A net rate of 324 Gbps under the 25% OH SD-FEC threshold was achieved with a PAM8 format for the QD-SOA and the PDFA. The QW and bulk SOAs achieved a net rate of 288 Gbps for PAM8 under the same FEC threshold. Fig. 3 c) presents the BER as function to the ROP at PAM4 152 GBaud. The QD-SOA performed best at that baud rate and a power penalty of 1.22 dB is measured for the PDFA to perform at the 20% OH SD-FEC threshold. The QW-SOA has a similar power penalty of 1.25 dB and the bulk SOA 1.6 dB for the same FEC threshold. At lower baud rates ($<$ 136 GBaud), the QD-SOA underperforms the PDFA because of the faster dynamic response of the former, resulting in data-pattern amplitude wandering at the SOA output [10]. As the baud rate increases, the impact of this effect diminishes, leading to a convergence in the amplifier's behavior. This effect is also enhanced by the high correlation present between the four launched symbol sequences and the nature of the PAM format (higher optical power variation in time as compared to coherent modulation formats). For the coherent transmission experiment, the QD-SOA achieved a net rate of 1015.1 Gbps under the 6.7% OH HD-FEC threshold, while the PDFA, QW and bulk SOAs achieved 870.4 Gbps under the 20% OH SD-FEC threshold for DP-16QAM. All four amplifiers achieved a net rate of 1020 Gbps under the 25% OH SD-FEC threshold for DP-32QAM. Finally, the QD-SOA outperformed all four amplifiers for DP-64QAM by achieving a net rate of 1224 Gbps under the 25% OH SD-FEC threshold. The QW-SOA and PDFA achieved a net rate of 1152 Gbps while the bulk achieved 936 Gbps under the same threshold. The smaller α-factor with the shorter GRT combined with the higher saturation power of the QD-SOA allow the QD-SOA to outperform the other SOAs, and the performance difference with respect to the PDFA grows in favor of the QD as the cardinality of the format increases. The maximal net rates achieved are summarized in Table 1. For coherent transmission, the QD-SOA outperformed all other amplifiers. For IM/DD, the QD-SOA and PDFA achieved the same net rate.

Table 1: Summary of achieved net bitrates for each amplifier per λ for coherent and IM/DD.

Amplifier	Modulation Format	Net Bitrate (Gbps)
PDFA	PAM8/144 Gbaud	324
	DP-64QAM/128 GBaud	1152
QD-SOA	PAM8/144 GBaud	324
	DP-64QAM/136 GBaud	1224
QW-SOA	PAM8/128 GBaud	288
	DP-64QAM/128 GBaud	1152
Bulk SOA	PAM8/120 GBaud	270
	DP-32QAM/136 GBaud	1020

4. Conclusion

We experimentally demonstrate that the QD-SOA outperforms the PDFA and other SOA technologies for multi-Tbps per λ transmission in the O-band. These results show that the QD-SOA is the key candidate for multichannel O-band integrated transceivers for both coherent and IM/DD.

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