Performance analysis of a directly modulated semiconductor optical amplifiers using non-return-to-zero, duobinary and quaternary pulse amplitude modulation signalling

Ramón Gutiérrez-Castejón | Osvaldo Fernández-Segura | Pablo Torres-Ferrera | Daniel Enrique Ceballos-Herrera

ABSTRACT
Numerical investigation was done for the response of two semiconductor optical amplifiers (SOA) to direct modulation using three of the most commonly employed intensity modulation formats: non-return-to-zero (NRZ), duobinary (DB) and quaternary pulse amplitude modulation (PAM-4). It was shown that an optimized SOA not only delivers an average optical power of 18 dBm, but can also be modulated at 25.4, 28.0 and 29.3 Gb/s with the aforementioned formats, respectively. No optical or electronic assistance is considered. The use of spectral-efficient PAM-4 thus leads to an improvement of almost 4 Gb/s with respect to NRZ. Slightly faster modulation is reached by operating the SOA deeper into saturation. These figures fall to 12.8, 15.0 and 16.3 Gb/s after 20 km conventional single-mode fibre propagation in C-band. Calculation of 10 Gb/s back-to-back sensitivities at the low-density parity-check forward error correction bit-error ratio (BER) threshold of $1 \times 10^{-2}$ resulted in $-24.5$, $-20.5$ and $-20.0$ dBm for NRZ, DB and PAM-4 modulations, with a 50 km transmission penalty lower than 3 dB for PAM-4. This enables the use of directly modulated SOAs as transmitter alternative in high-loss access networks, such as super-passive optical networks, provided that further technical improvements can be performed to meet its challenging loss budget.

1 INTRODUCTION
The design and eventual implementation of an opto-electronic transmitter exhibiting relatively broad bandwidth (BW) and high output power, packaged in a small integrated photonic circuit, is always welcome as a key element of an intensity-modulated with direct-detection (IM-DD) unamplified optical fibre system. These elements are useful not only because they help to fulfil the power budget requirements of the system, but because their employment normally reduces the overall power expenditure of the network. One relevant example of the need for these elements is found in the realm of short-reach systems. In particular, in time-division multiplexed passive optical networks (TDM-PONs), where the introduction of this kind of transmitters may help to increase the power budget margins.

Indeed, due to the point to multi-point nature of these networks and despite that they should only reach 20 km of conventional single-mode fibre (CSMF), these architectures rely on meeting a loss budget of at least 29 dB (PR30 in EPON, N1 class in ITU-T-PON) [1]. This tight budget requirement comes from their inherent 1:32 power splitter, necessary to build their tree topology. Even more challenging is the implementation of a Super-PON, which is currently under development by the IEEE P802.3cs Task Force [2] and the ITU through recommendation G.9807.3 [3]. This multi-wavelength PON architecture is expected to support a bit rate of 10 Gb/s following a passive point-to-multipoint topology (relying on a passive wavelength router) where a transmission reach of at least 50 km has been set as objective [4]. With its increased reach and an aggregation of up to 1024 customers, Super-PON is...
especially attractive as a solution to provide a competitive bandwidth to more sparsely populated areas. Among several design challenges, a loss budget of 41 dB (without considering fibre impairments) has to be surmounted using multi-wavelength amplification and optical receivers with sensitivities lower than −30 dBm (non-return-to-zero [NRZ] format) [5]. As an alternative to Er-doped fibre amplifiers (EDFAs), currently being considered [4], the use of 10 Gb/s powerful transmitters might be attractive in terms of cost and power consumption savings. Current state-of-the-art 10 Gb/s transmitters relying on semiconductor optical amplifier (SOA) boosters deliver an output power of about 9 dBm [6]. Higher transmission power, nonetheless, can be produced by directly modulating an SOA that uses a low-power continuous wave (CW) laser as optical input. In this scheme, the SOA’s pumping current is modulated by a radio-frequency data signal that in turn modifies the gain (and refractive index) of the amplifier. Correspondingly, the originally CW signal becomes simultaneously amplified and modulated, resulting, in the ideal situation, in an optical replica of the digital information to be transmitted. Nevertheless, this approach suffers from a very low opto-electronic BW [7], mainly determined by the relatively long differential carrier lifetime that is characteristic of the SOA [8]. An opto-electronic BW of a few GHz leads to data-pattern degradation [9] in 10+ Gb/s systems. Although customization of the SOA structure and proper adjustment of the operation point improves the SOA modulation BW [10], more practical solutions to tackle this limitation are based on serially connecting an offset optical filter into the SOA output to tailor the chirp dynamics of the outgoing optical waveform, thus reducing the undesired distortions [11]. Some already explored filtering configurations are summarized in Table 1. Unfortunately, this all-optical approach integrates an extra element (the filter) into the transmitter. This increases complexity and unwelcome insertion losses, which sometimes even overcome the gain produced by the SOA [9]. An alternative approach to prevent this, but yet augment the transmission bit rate, is to use advanced modulation formats, characterized by exhibiting a high spectral efficiency (instead of using plain NRZ format). Duobinary (DB) modulation, produced by filtering an XOR-precoded NRZ sequence with the aid of a fourth order Bessel electrical filter whose BW matched 0.25 × B, has been tested at a bit rate B = 10 Gb/s, producing encouraging results. In the experiment, the corresponding electrical signal was employed to directly modulate a reflective SOA (RSOA) exhibiting an opto-electronic BW of 1.5 GHz. Thanks to its narrow BW and the fibre chromatic dispersion tolerance inherent to DB modulation, 10 km transmission was effectively demonstrated in C-band [12].

Due to its relative compact spectrum and its ease of implementation (e.g. as compared to coherent modulation) pulse-amplitude modulation of 4 levels (PAM-4) has attracted considerable attention in recent years [18]. It has, for example, substituted NRZ as de facto modulation format in the Ethernet standard, as it moves its data rate from 100 Gb/s (4 × 25 Gb/s) to 400 Gb/s (8 × 50 Gb/s) [19]. Despite its benefits, however, PAM-4 has not been sufficiently investigated as an alternative to directly modulate an SOA. In [20], Cho et al. analysed the transmission performance of a PAM-4 encoded signal when an RSOA, exhibiting an opto-electronic BW of 2.2 GHz, was employed as optical modulator. The authors achieved 20 km reach at a bit rate of 11 Gb/s in C-band. Aided by electronic equalization (7-tap FFE and 5-tap DFE) and proper adjustment of the four amplitude levels, the authors measured a sensitivity of about −13 dBm at a bit-error ratio (BER) of 1 × 10^{-2}. Following this promising outcome, it results natural to ask whether PAM-4 can outperform DB modulation when utilized as coding technique to drive an SOA-based modulator. The question becomes particularly relevant when noting that the spectral BW of a PAM-4 signal is narrower than the corresponding one of a DB signal operating at the same bit rate. Indeed, Figure 1 shows the power spectral density of three electrical signals running at 10 Gb/s that are encoded using different modulation formats: NRZ, DB and PAM-4. The corresponding 3 dB BWs are, respectively, 4.0, 2.4 and 2.0 GHz. Clearly, the modulation with the broadest BW is NRZ, while that with the narrowest BW is PAM-4 and hence it should present the best performance when used to directly modulate an SOA, at least in back-to-back (BrB) configuration.

To test our hypothesis, in this contribution we present a system performance comparison as a function of bit rate of the three aforementioned modulation formats when they are employed to drive an SOA-based modulator. By means of simulations, carried out under the same system conditions, BrB and 20 km reach configurations are numerically analysed for two SOAs, each exhibiting different opto-electronic BW. It is shown that PAM-4 modulation indeed represents the best

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**Table 1** Review of filtering techniques employed to speed up the response of a directly modulated SOA

| Filter type         | Modul. format | B [Gb/s] | SOA Structure | Reference |
|---------------------|---------------|----------|---------------|-----------|
| Delay interferometer| NRZ           | 10       | RSOA          | [13]      |
| AWG                 | NRZ           | 10       | RSOA          | [14]      |
| Fibre bragg grating | NRZ           | 10       | RSOA          | [15]      |
| MZIs                | NRZ           | 10       | RSOA          | [16]      |
| μ-ring resonators   | RZ            | 10       | SOA           | [17]      |
| Double-stage BFL    | NRZ           | 5        | SOA           | [9]       |

Abbreviations: AWG, arrayed waveguide grating; BFL, birefringent fibre loop; MZI, Mach-Zehnder interferometer; NRZ; non-return-to-zero; RSOA, reflective semiconductor optical amplifiers; RZ, return-to-zero; SOA, semiconductor optical amplifiers.
choice to extend the operation speed of directly modulated SOAs, especially when transmission along an optical fibre is taken into account. In contrast, NRZ performs rather poorly. Bit rates as high as 29.3 (BtB) and 16.3 (20 km propagation) using PAM-4 can be achieved. These results are complemented with simulations using both SOAs to determine the system sensitivity for all three formats at 10 Gb/s. BtB, 20 and 50 km configurations are investigated and the corresponding power budgets calculated. The feasibility of implementation of 10G PONs, 25G PONs, and Super-PONs using directly modulated SOA transmitters is briefly discussed. This article is divided into four main sections. In Section 2, we explain how the simulations were carried out, including some SOA characterization curves derived from the numerical model (Section 2.2). Next in Section 3, we present and discuss the chief results of our analysis. Transmission speed (Section 3.1) and system sensitivity at 10 Gb/s (Section 3.2) are investigated. We conclude in Section 4.

2 | SYSTEM SETUP AND SIMULATION DETAILS

The system to be simulated, implemented on a VPI Design Suite™V10.0-Matlab®R2019a co-simulation platform, is presented in Figure 2. It consists of a travelling-wave SOA whose optical input is derived from a CW laser emitting at $\lambda = 1550$ nm with 10 MHz linewidth. The optical signal-to-noise ratio (OSNR) of the CW signal, prior to entering into the SOA, was set to 40 dB. The directly modulated SOA is driven using an electrical transmitter whose implementation details depend on the analysed modulation format, but includes a pseudo-random bit sequence (PRBS) generator, an encoder (with preceding in the DB case), an upsampling module that acts as digital-to-analogue converter and a driver that sets bias and amplification of the driving (pumping) signal. In all transmission cases, the same PRBS, $2^{16}$ bits long, was encoded using NRZ, DB or PAM-4 formats. The sequence was then upsampled 64 times to simulate an electrical signal varying between 200 and 600 mA, irrespective of modulation format. In this way, we maintained the same (outer) extinction ratio in all cases. The characteristics of the SOA are discussed below. Depending on the state of a simple switch, the modulated optical signal is launched onto 0 (BtB case), 20 km or 50 km of (CSMF), which is modelled following a uni-directional time-domain formalism. The fibre model considers chromatic dispersion and Kerr non-linearities. For $\lambda = 1550$ nm, the fibre parameters were chosen as: attenuation of 0.25 dB/km, dispersion of 17 ps/nm-km, slope of 0.08 ps/nm$^2$/km, non-linear index of $2.6 \times 10^{-11}$ $\mu$m$^2$/mW and a core effective area of 80 $\mu$m$^2$. After fibre transmission, a variable optical attenuator (VOA) is introduced to control the power impinging into the optical front end (OFE). The OFE consists of a PIN photodiode and a trans-impedance amplifier (TIA). The photodiode model, having a responsivity of 0.9 A/W, takes into account shot noise and thermal noise with a current noise density of 14 pA/$\sqrt{Hz}$ and a dark current of 5 nA. It has an optoelectronic 3-dB BW of $0.75 \times B$ Hz with Bessel characteristics, where B stands for the system bit rate. The TIA has a conversion gain of 4000 $\Omega$ and a noise current of 1.1 $\mu$A that captures all noise sources of the TIA. After clock-recovery, optimization of the decision threshold in both the horizontal (time) and vertical (voltage) directions is carried out, followed by decoding of the corresponding modulation format. The BER is finally calculated by direct bit counting. According to this conventional procedure to calculate the BER, $1.81 \times 10^{-4}$ becomes the minimum BER that we can report with a confidence level of 95% [21]. This estimation can be determined from the safety margin of maximum allowed mistakes incurred while counting the bits, that we have set to six; and the number of transmitted bits ($2^{16}$) employed to carry out the error counting calculations, which in turn is limited by computational time and memory constraints.

2.1 | SOA modelling

Modelling of the bulk SOA was carried out with the most sophisticated SOA module provided by VPI. It is based on a well-tested, multi-section transmission line model [22] that takes into account the longitudinal distribution of the carrier density and the propagation of the optical waveform (fundamental mode) along the device. The calculation of the former is based on conventional rate equations that include ultra-fast non-linear effects. The latter is simulated via scattering matrices acting upon a forward and backward propagated (complex) optical field that travels along the transmission lines that interconnect the sections in which the SOA is divided. We have assumed a current injection efficiency of 100% that is homogeneously distributed along the SOA, and we have disregarded some electro-optical parameters in the SOA model such as capacitances, inductances, and resistances inherent to the SOA assembly [23]. These assumptions might lead to small
inaccuracies that are inconsequential for the results reported in this work. Modelling of the carrier density-dependent amplified spontaneous emission (ASE) is included in the formalism. It uses Langevin noise sources scaled by means of a population inversion parameter. The refractive index dynamical behaviour is captured through the use of the well-known linewidth enhancement factor [24]. Since only one wavelength is considered in the analysis, we selected the flat gain dispersion model. The SOA photonic module accepts three ports: optical input, optical output, and electrical input. The modulated electrical signal is injected into the latter, which in turn modifies the carrier injection density (pumping), being responsible for generation of electron-hole pairs inside the active region. The carrier injection density represents a fundamental (for our analysis) term in the carrier density rate equation, which is also mediated by the recombination rate and stimulated emission rate. When the recombination rate is associated to a carrier lifetime [8], it determines the response time, and hence, the opto-electronic bandwidth of the active device. If the period of the transitions with which the carriers are injected becomes much lower than the response time of the SOA, the originally modulating signal becomes severely low-pass filtered (LPF) and distorted when transformed to a variation of the carrier density, or SOA gain. This in turn generates a distorted optical waveform with respect to the injected modulating signal. Further details of the modelling approach can be found elsewhere [25]. Table 2 lists the parameter values used with the SOA model in our simulations. Two sets of parameters are considered. The set corresponding to SOA1 refers to a standard bulk SOA, whereas the set of parameter values corresponding to SOA2 has been fine-tuned to match an amplifier that exhibits a faster response while maintaining similar gain characteristics, as demonstrated in the next subsection.

2.2 | Numerical characterization of the SOA

Before carrying out the main analysis of our contribution, it is always convenient to characterize some aspects of the amplifiers. This procedure is useful to set the most adequate SOA operation region. The derived curves are also helpful as a reference point for the interpretation of the results presented in Section 3. This analysis also provides confidence in the modelling approach and the actual parameter selection (see Table 2). Figure 3 displays the on-chip SOA gain as a function of input (red) and output (blue) power for a constant injection current value of 300 mA. Results for SOA1 (solid) and SOA2 (dashed) are presented. The curves follow the expected saturation behaviour [26]. Small-signal gains of 34.7 and 35.5 dBm are measured from the graphs for SOA1 and SOA2, respectively. Of particular interest is the input saturation power of SOA1 that corresponds to $P_{in}^{sat} = -22$ dBm, whereas $P_{out}^{sat} = 9.5$ dBm. Similar values can be measured for SOA2.

Figure 4 presents the SOA output power ($P_{out}$) as a function of constant injection current for different values of input power ($P_{in}$) calculated using SOA1. As expected, once we reach the current required to produce sufficient gain to overcome the device losses, the optical output power ($P_{out}$) starts growing in a practically linear fashion. For the same current level, higher $P_{out}$ is obtained for higher $P_{in}$, although gain saturation is effectively observed as $P_{in}$ becomes more intense. Very similar curves (not shown) are obtained for SOA2. Output powers as high as 80 mW are calculated for 400 mA at $P_{in} = 10$ dBm, corresponding to a gain of 9 dB. The gain becomes higher (about 18.5 dB) for a more reasonable $P_{in} = 0$ dBm that produces a $P_{out} = 70$ mW. This demonstrates the advantage in terms of output power that the use of an SOA as optical modulator offers. When SOA2 is employed with $P_{in} = 0$ dBm, the output power at 400 mA decreases to 63 mW, corresponding to an amplifier gain of 18 dB. As Figure 3 confirms, SOA2 exhibits a slightly lower gain than SOA1 at $P_{in} = 0$ dBm because of its marginally lower saturation power.

Particularly relevant for this work is the modulation BW analysis of the amplifiers. This is achieved by injecting a sinusoidal electrical signal into the SOA that varies from 300 to 400 mA (here the $P_{out}$ v.s. injection current curve behaves practically linear) and then measure the peak-to-peak power of the optical signal obtained at the SOA output while the frequency of the input periodic signal increases. The corresponding normalized curves for different values of $P_{in}$ are
better performance of the directly modulated SOA is obtained when a strong CW beam is employed. Unfortunately, it is also at this operation point that the amplifier delivers a compressed gain, thus downgrading the main benefit of using an SOA as modulator. A compromise between high gain and broad modulation BW has to be set. For the simulations presented in Section 3, two values of $P_{in}$ were considered: 0 and 10 dBm since, according to Figures 5 and 6, they lead to a similarly fast modulation response. Clearly, in both cases the amplifier operates well in its saturation regime (see Figure 3). Figure 6 is also useful to point out the broader optoelectronic BW becomes shorter than 2 GHz in SOA1, for $P_{in} = 10$ dBm, the same performance parameter becomes approximately 4.3 GHz. This behaviour can be ascribed to the higher saturation level presented by the SOA when a high input optical power is introduced. Indeed, when the SOA becomes saturated, its effective carrier lifetime decreases, leading to a faster response and broader BW of the device (see, e.g. [26], p. 99). The practical consequence of this observation is that better performance of the directly modulated SOA is obtained when a strong CW beam is employed. Unfortunately, it is also at this operation point that the amplifier delivers a compressed gain, thus downgrading the main benefit of using an SOA as modulator. A compromise between high gain and broad modulation BW has to be set. For the simulations presented in Section 3, two values of $P_{in}$ were considered: 0 and 10 dBm since, according to Figures 5 and 6, they lead to a similarly fast modulation response. Clearly, in both cases the amplifier operates well in its saturation regime (see Figure 3). Figure 6 is also useful to point out the broader optoelectronic BW becomes shorter than 2 GHz in SOA1, for $P_{in} = 10$ dBm, the same performance parameter becomes approximately 4.3 GHz. This behaviour can be ascribed to the higher saturation level presented by the SOA when a high input optical power is introduced. Indeed, when the SOA becomes saturated, its effective carrier lifetime decreases, leading to a faster response and broader BW of the device (see, e.g. [26], p. 99). The practical consequence of this observation is that

| Parameter                 | SOA1 | SOA2 | Units | Reference |
|---------------------------|------|------|-------|-----------|
| Active region length      | 2.0  | 2.0  | mm    | [11]      |
| Active region width       | 2.8  | 2.8  | μm    | [8]       |
| Active region thickness   | 0.25 | 0.25 | μm    | [8]       |
| Internal loss             | 1000 | 1000 | m$^{-1}$ | A.C.A.   |
| Confinement factor        | 0.25 | 0.4  |       |           |
| Differential gain         | 3.3×10$^{-20}$ | 5.3×10$^{-20}$ | m$^2$ | [8,11]   |
| Carrier density at transp.| 0.60×10$^{-24}$ | 0.46×10$^{24}$ | m$^{-3}$ | A.C.A.   |
| Leakage Recomb. Coef.     | 6.0×10$^8$ | 6.0×10$^8$ | 1/s | [26]     |
| Bimolecular Recomb. Coef. | 3.0×10$^{-16}$ | 18.0×10$^{-16}$ | m$^3$/s | [26]   |
| Auger Recomb. Coef.       | 1.0×10$^{-40}$ | 1.0×10$^{-40}$ | m$^6$/s | [26] |
| Linewidth enhancement factor | 3.0 | 3.0 |       | A.C.A.   |

Abbreviations: A.C.A, Around commonly accepted value; SOA, semiconductor optical amplifiers.

**FIGURE 3** On-chip SOA gain versus input (red) and output (blue) power for SOA1 (solid) and SOA2 (dashed). The corresponding 3-dB saturation powers are highlighted with dotted lines. \( P_{sat}^{in} = -22 \) dBm, \( P_{sat}^{out} = 9.5 \) dBm. SOA, semiconductor optical amplifiers

**FIGURE 4** Power calculated at the output of SOA1 as a function of constant injection current for different values of CW input optical power. CW, continuous wave; SOA, semiconductor optical amplifiers.
transmission rates. Finally, for the selected values of $P_{in}$, we will vary the modulated driving current between 200 and 600 mA because at this operation point, and under ideal conditions of infinite opto-electronic BW, a one-to-one mapping between the electrical and optical signals should take place, as shown by the linear region of Figure 4.

3 | TRANSMISSION RESULTS

3.1 | Transmission speed analysis

We carried out transmission simulations following the scheme presented in Figure 2. NRZ, DB and PAM-4 signalling were analysed. In order to guarantee a fair comparison among all formats and system configurations, and to avoid the overload of the photodiode (PD) at the receiver end, in all the situations analysed in this section we have set the received optical power (ROP) at the PD input to $-5$ dBm. The VOA was then set accordingly in each case. The electrical spectra of the three modulation formats with all signals running at 10 Gb/s and captured prior to entering into the SOA, are displayed in Figure 1. As discussed in the introduction, the narrowest spectrum corresponds to PAM-4. Due to its inherent 2 bits-per-symbol coding scheme, a sharp decrease on its power spectrum becomes evident, showing a local minimum at 5 GHz, which corresponds to the symbol rate (5 Gbd). NRZ has the broadest spectrum, with a 3-dB BW two times wider than PAM-4. Being a spectrally compressed version of NRZ, DB modulation shows a spectrum that decreases faster than NRZ, but still it is slightly broader than the spectrum of PAM-4. In this respect, it is worth mentioning that the DB signal was generated using a fifth-order Bessel electrical LPF showing a 3-dB cut-off frequency of $0.33\times B$. We noticed that this choice of BW offered the best results.

Figure 7 shows the BER versus B curves resulting from simulations in BitB configuration when SOA1 is employed. First, a CW beam having an input power of 0 dBm (solid line) was injected into the SOA, leading to an optically modulated output signal exhibiting an average power of 18.6 dBm (about 72.4 mW), irrespective of modulation format. This corresponds to an SOA gain of 18.6 dB. Our calculations hence demonstrate the benefit in terms of output power that using the SOA as modulator provides, showing its superior performance over other solutions (e.g. the AXEL [6]). The solid curves in Figure 7 show a pronounced increase of BER as a function of bit rate. All formats exhibit similar slopes.
According to the figure, the best performance for a BER of $1 \times 10^{-2}$ (see explanation below) is presented by PAM-4 (yellow curve) since the use of this format leads to the highest modulation speed. It is closely followed by DB modulation (blue curve), which even surpasses the performance of PAM-4 at low BER values. NRZ (red curve) shows the worst performance from the three analysed signalling schemes. Our numerical results then confirm our hypothesis: PAM-4, the modulation format with the narrowest spectrum, reaches the highest modulation speed, whereas NRZ, the modulation format with the broadest spectrum, achieves a rather modest bit rate. This observation can be explained as follows. Since, according to Figure 5, and due to its inherent carrier density dynamics, the SOA acts as a transducer with LPF characteristics, it results natural to expect higher transmission speeds when a format with a narrower spectral shape is employed. In other words, PAM-4 results less distorted by the BW-limiting characteristics of the SOA with respect to NRZ; consequently, lower BER values are achieved for a given bit rate. To quantitatively determine the performance difference among the analysed formats, we have set $1 \times 10^{-2}$ as our reference BER. This value corresponds to the low-density parity-check forward error correction (LDPC-FEC) threshold [27]. For this BER value, the maximum bit rates that can be achieved by each format are presented in Table 3 (first row): 12.8 Gb/s for NRZ, 14.0 Gb/s for DB and 14.5 Gb/s for PAM-4. From these numbers it is evident that the use of PAM-4 signalling provides a bit rate extension of 0.5 Gb/s with respect to DB and even more, 1.7 Gb/s, with respect to NRZ modulation, thus demonstrating the advantage of using PAM-4 to increase the operational speed of a directly modulated SOA transmitter. This increase in transmission speed is simply achieved by switching to a modulation format having a higher spectral efficiency. No further optical or electronic assistance is employed.

As already predicted with the aid of Figure 5, higher bit rates are expected when increasing the CW power injected into the SOA. Under these operation conditions, the amplifier is more deeply driven into saturation, shortening its effective carrier lifetime [8]. This can be confirmed using our simulation platform by setting $P_{in} = 10$ dBm. As the dot-dashed lines in Figure 7 show, the corresponding values of B at $BER = 1 \times 10^{-2}$ are now 16.0 Gb/s for NRZ, 18.1 Gb/s for DB and 18.4 Gb/s for PAM-4. See also the second row of Table 3. This represents an increase as compared to the $P_{in} = 0$ dBm case, of 3.2, 4.1, and 3.9 Gb/s for NRZ, DB and PAM-4 modulations, respectively. This approximately uniform increase in bit rate leads to an effective shift of the three BER versus B curves along the B axis. It does not markedly affect their shapes. What it is more relevant to our analysis, however, is the fact that in spite of the increase of $P_{in}$, PAM-4 modulation preserves the best performance, while NRZ remains the less favoured among the analysed formats. The increase in operational bit rate observed in all formats, nonetheless, comes with a penalty in amplifier gain. Indeed, according to Table 4, $P_{out}$ now amounts to 19.2 dBm, which corresponds to a gain of only 9.2 dB, instead of 18.6 dB measured for the $P_{in} = 0$ dBm case. Although $P_{out} = 19.2$ dBm can be considered a relatively high output power, an input power of 10 dBm is still difficult to achieve with standard laser diodes. $P_{in} = 0$ dBm is hence a more sensible choice, even though the consequent reduction in bit rate and the minor decrease in output power, of only 0.6 dB.

In the light of the aforementioned results, it is worth investigating the performance of each signal when propagated along an optical fibre, especially because DB and PAM-4 modulations are known to be chromatic dispersion tolerant [28,29]. Figure 7 shows, in dashed lines, curves of BER versus B for the three analysed modulation formats. They were produced via simulations where $P_{in} = 0$ dBm (as the solid curves), but following the 20 km optical fibre path shown in Figure 2. We chose a fibre length of 20 km since it is the target reach of current PONs [1]. Similarly to previous analyses, the VOA is set so the ROP amounts to $-5$ dBm. The fibre model accounts for fibre dispersion and non-linear effects (see Section 2). The average input power into the fibre is 18.6 dBm, as indicated in the third row of Table 4. According to Figure 7, the effect of fibre propagation in all signals is to increase distortions and hence augment the BER for a given bit rate value. Again, all curves approximately maintain their shape but they appear shifted towards lower bit rates. Taking $BER = 1 \times 10^{-2}$ as reference performance level, the bit rates after 20 km propagation are the following: 9.8 Gb/s for NRZ, 11.0 Gb/s for DB and 11.3 Gb/s for PAM-4. They are also presented in the third row of Table 3. Our simulation results demonstrate that, although a directly modulated SOA-based transmitter can effectively be employed in 10 Gb/s systems with maximum reach of 20 km, care has to be taken in choosing the most adequate operating conditions and modulation format.

**Table 3** Bit rate [Gb/s] at the LDPC-FEC BER threshold for different combinations of CW power injected into the SOA ($P_{in}$) and fibre length (L).

| $P_{in}$ [dBm] | L [km] | SOA1 | SOA2 |
|---------------|-------|------|------|
|               |       | NRZ  | DB   | 14.5 | PAM-4  |
|               |       | NRZ  | DB   | 14.5 | PAM-4  |
| 0             | 0     | 12.8 | 14.0 | 14.5 | 25.4   |
| 10            | 0     | 16.0 | 18.1 | 18.4 | 31.0   |
| 0             | 20    | 9.8  | 11.0 | 11.3 | 12.8   |

**Table 4** SOA output power ($P_{out}$) in [dBm] for different combinations of CW power injected into the SOA ($P_{in}$) and fibre length (L). $P_{out}$ is independent of the modulation format.

| $P_{in}$ [dBm] | L [km] | SOA1 | SOA2 |
|---------------|-------|------|------|
| 0             | 0     | 18.6 | 18.2 |
| 0             | 20    | 18.6 | 18.2 |

Abbreviations: BER, bit-error ratio; CW, continuous wave; DB, duobinary; LDPC-FEC, low-density parity-check forward error correction; NRZ, non-return-to-zero; PAM-4, quaternary pulse amplitude modulation; SOA, semiconductor optical amplifiers.
instance, whereas in our simulations PAM-4 is capable of reaching bit rates well above 10 Gb/s, NRZ falls short in this respect, favouring the choice of the former signalling scheme.

After fibre propagation, Figure 7 shows that PAM-4 modulation barely keeps its prominence, whereas NRZ again exhibits the worst performance. When the obtained bit rates are compared to the BtB ones (first row in Table 3), the following differences are observed: 3 Gb/s for NRZ and DB modulations and 3.2 Gb/s for PAM-4. That means that for 340 ps/nm of accumulated dispersion, corresponding to 20 km of CSMF in C band, the maximum bit rate achievable by all analysed formats becomes affected by chromatic dispersion in practically the same manner. Note, however, that favourable noise conditions (high SNR at the receiver), resulting from a high value of $R_{OP} = -5$ dBm, prevail. Further reductions in B can be anticipated as the fibre length increases, thus effectively limiting the system reach. In general, the degradation observed in the optical signal due to chromatic dispersion is expected to be higher as compared to the externally modulated situation because of the presence of chirp and distortions imprinted in the optical signal by the directly modulated SOA. A comparison analysis following these lines and considering varying fibre lengths, is still necessary to be done. This topic is, nevertheless, out of the scope of this report. Let us just mention that the use of a chirp management element, for instance, an optical filter (see Table 1), will most probably be helpful to extend the reach of a directly modulated-based transmission system operating at a given bit rate. Equivalently, lower penalties in terms of bit rate are expected in this kind of chirped-managed transmission systems at a given fibre length.

The overall performance of the 20 km long fibre system can be improved by running simulations with an input power into the SOA of 10 dBm (instead of 0 dBm). For the sake of brevity, these results have been omitted, but they can be qualitatively inferred based on our previous numerical analyses. Indeed, the expected outcome is a uniform shift of the dashed curves shown in Figure 7 to higher B values, where PAM-4 modulation will maintain the highest bit rate at the LDPC-FEC BER threshold, while NRZ will keep the lowest bit rate. Furthermore, it is not difficult to foresee that NRZ will now be able to operate at 10 Gb/s since an increase of only 0.2 Gb/s suffices to reach this relevant transmission speed. The 20 km system would hence become benefited from the increase on input power. Similarly, the SOA output power under these circumstances of input power can be predicted to be 19.2 dBm, irrespective of modulation format (see Table 4). This value is slightly higher than the one obtained using $P_{in} = 0$ dBm (i.e. $P_{out} = 18.6$ dBm).

Our transmission speed analysis can be extended by considering simulations employing SOA2. According to Section 2.2, this SOA exhibits similar gain levels to those presented by SOA1, while displaying a faster response time. A 3-dB BW more than two times higher than that determined for SOA1 was measured from Figure 6. Consequently, higher transmission speeds are expected when running simulations similar to those described above. The corresponding results are graphically presented in Figure 8 and summarized in the rightmost columns of Tables 3 and 4. According to the latter, the calculated power at the SOA output is indeed very similar to the one determined for SOA1, only approximately 0.5 dB lower. More relevant results can be read from Figure 8. First, we can observe that when measuring the bit rate at the LDPC-FEC threshold and, in agreement with our results for SOA1, it is PAM-4 (yellow curves) the modulation format that exhibits the best performance in all three analysed situations: BtB with $P_{in} = 0$ dBm, BrB with $P_{in} = 10$ dBm, and 20 km CSMF propagation with $P_{in} = 0$ dBm; while NRZ is still the least favoured one. Bit rate differences between PAM-4 and NRZ modulation formats amount to 3.9, 5.7, and 3.5 Gb/s for the three analysed cases, respectively (see Table 3). They represent the transmission speed gained when switching from NRZ to PAM-4. These bit rate extensions are higher than those calculated using SOA1 (1.7, 2.4, and 1.5 Gb/s, respectively). Second, we can observe that, although shifted towards higher B values, the shapes of the BER versus B curves are, in general, preserved. Third, irrespective of modulation format, the highest transmission speeds are obtained for the most powerful input beam (dot-dashed lines), followed by the $P_{in} = 0$ dBm case (solid lines), while the lowest modulation speeds correspond to the fibre transmission case (dashed lines). This behaviour is in line to what we observed when using SOA1. And fourth, faster bit rates are indeed found for all the analysed situations and modulation formats as compared to those calculated using SOA1. In particular, for both BbB cases, B is always greater than 25 Gb/s, even when using NRZ format with $P_{in} = 0$ dBm (see upper rows of Table 3). This means that properly optimized directly modulated SOA transmitters can, in principle, be employed in 25G fibre links. Unfortunately, optical signals modulated with higher B are
also more severely affected by chromatic dispersion and other deleterious fibre effects. Therefore, after 20 km fibre transmission, the maximum achievable B becomes reduced to levels varying from 12.8 Gb/s for NRZ to 15.0 Gb/s for DB and 16.3 Gb/s for PAM-4. Although they are still higher than those obtained with SOA1, they are only fast enough to be used in 10G systems. The situation might be different in dispersion-managed photonic links, or those with channel plans laying in O-band, which are characterized by low chromatic dispersion and high fibre loss. There, high transmission speeds can be preserved, while the corresponding increase in loss budget can be compensated with the high output power delivered by the SOA-based transmitter.

3.2 Sensitivity analysis

From the application standpoint, it is always welcome the calculation of the system sensitivity under particular conditions of bit rate and transmission distance. This allows the determination of power penalties and, ultimately, of the system power budget, which is an essential metric to decide on the technical feasibility of an optical link. Since the envisaged applications in this work are PONs and, in particular, Super-PONs, we have carried out a sensitivity analysis of the directly modulated SOA system depicted in Figure 2 for three different fibre lengths: 0, 20 and 50 km. We have opted for a CW input power of 0 dBm, which seems to be more akin to commercial applications in this work are PONs, and, in particular, Super-PONs, we have carried out a sensitivity analysis of the directly modulated SOA system depicted in Figure 2 for three different fibre lengths: 0, 20 and 50 km. We have opted for a CW input power of 0 dBm, which seems to be more akin to commercial applications. For the same reason, we have chosen a bit rate of 10 Gb/s, which operates at $B = 10$ Gb/s, with a maximum fibre length of 50 km. The analysis has been conducted for NRZ, DB and PAM-4 formats and we have included both investigated SOAs in our calculations.

Figure 9 displays the BER versus ROP curves obtained from our simulations when employing SOA1. The ROP is varied by accordingly setting the losses of the VOA placed before the PIN photodiode. Curves for the BtB (solid), 20 km (dashed) and 50 km (dot-dashed) configurations are presented. For the bit rate of choice, and in agreement with Figure 7, when a signal with NRZ format (red curves) is transmitted along 20 and 50 km long fibres, it becomes severely distorted such that the corresponding BER values cannot be accurately calculated (hence, the values are not displayed in the figure). In contrast, when operated in BtB configuration, NRZ presents the lower sensitivity value of all formats. The situation is different with DB and PAM-4 formats, which, although exhibiting a higher distortion level than NRZ (and thus higher BER values) when coming out from the SOA (or BtB case), they become less affected by fibre propagation effects. This is particularly evident in PAM-4. Table 5 summarizes, for all the analysed formats, the sensitivities measured at the LDPC-FEC BER threshold. It quantitatively confirms our findings. Whereas NRZ presents a BtB sensitivity of $-20$ dBm, the calculated sensitivities for DB and PAM-4 modulation amount to $-17.9$ and $-18.5$ dBm, respectively. However, the power penalties with respect to BtB of DB and PAM-4 formats are 1.0 and 1.6 dB, respectively, for 20 km propagation and a very large value (floor observed) and 6.5 dB for 50 km propagation. This indicates that, when SOA1 is employed for transmitting at 10 Gb/s, NRZ should be the format of choice only when systems having a very short reach (a few kilometres) are considered, whereas PAM-4 should be used in systems with fibres no longer than about 50 km, accepting the corresponding power penalty.

![Simulated BER performance as a function of received optical power of the system shown in Figure 2 using SOA1 for 0, 20 and 50 km transmissions at 10 Gb/s with NRZ, DB and PAM-4 modulations. The LDPC-FEC BER threshold is marked with a horizontal line. BER, bit-error ratio; DB, duobinary; LDPC-FEC, low-density parity-check forward error correction; NRZ, non-return-to-zero; PAM-4, quaternary pulse amplitude modulation; SOA, semiconductor optical amplifiers](image)

**TABLE 5** Sensitivity at BER = $1 \times 10^{-2}$, SOA output power and corresponding power budget for links 0, 20 and 50 km long, and for NRZ, DB and PAM-4 modulation formats. Simulations performed using SOA1 at 10 Gb/s

| Format | BER | 20 km | 50 km |
|--------|-----|-------|-------|
| NRZ    | $-20.0$ | Distor$^a$ | Distor$^a$ |
| SOA output power [dBm] | 18.6 | 18.6 | 18.6 |
| Power budget [dB] | 38.6 | 0 | 0 |
| DB     | $-17.9$ | $-16.9$ | Floor$^b$ |
| SOA output power [dBm] | 18.6 | 18.6 | 18.6 |
| Power budget [dB] | 36.5 | 35.5 | 0 |
| PAM-4  | $-18.5$ | $-16.9$ | $-12.0$ |
| SOA output power [dBm] | 18.5 | 18.5 | 18.5 |
| Power budget [dB] | 37.0 | 35.4 | 30.5 |

Abbreviations: BER, bit-error ratio; BtB, back-to-back; DB, duobinary; NRZ, non-return-to-zero; PAM-4, quaternary pulse amplitude modulation; SOA, semiconductor optical amplifiers.

$^a$Distor means that the signal is too distorted to calculate its BER.

$^b$Floor means that, for all calculated ROP values, BER > $1 \times 10^{-2}$. 
Based on the calculated sensitivities and the high output power delivered by the directly modulated SOA (also shown in Table 5), the available power budget can be calculated for each modulation format. It is the difference (in dB) between the measured sensitivity and the SOA output power and is also displayed in Table 5. For the BtB configuration, the available power budgets are 38.6 dB (NRZ), 36.5 dB (DB) and 37.0 dB (PAM-4). Clearly, none of them is sufficient to meet the loss budget of 41 dB associated to Super-PON, especially after having considered the corresponding 50 km transmission power penalty. This is not the case, however, when considering 10 Gb/s PONs, where a loss budget of 29 dB (PR30 in EPON and N1 class in ITU-T-PON) and a transmission distance of 20 km can be readily bridged by DB and PAM-4 formats. Indeed, the available power budget in this case (20 km) is slightly greater than 35 dB for both formats. It is, therefore, 6 dB higher than strictly necessary by N1 class PONs, thus enabling other PON classes with higher required power budget. Curiously, due to limitations inherent to the SOA-based modulation approach, NRZ cannot be employed for the implementation of this kind of networks. This fact, together with the simplicity of directly modulated lasers [30], turn the directly modulated SOA approach into an impractical solution for 10G PONs.

The sensitivities presented in Table 5 for both, BtB and fibre propagation, are very dependent on the particular SOA characteristics. Among them, we can mention bandwidth and saturation power. Therefore, better overall system performance can be expected when using SOA2. To demonstrate this projection, we have carried out a similar 10 Gb/s sensitivity analysis, but this time using SOA2. The results are presented in Figure 10, whereas the corresponding power calculations and sensitivities measured at the LDPC-FEC BER threshold are shown in Table 6. Thanks to the broader BW exhibited by SOA2, a less distorted optical signal emerges from the amplifier output facet and hence, the measured sensitivity values are, in general, lower. Such is the case of NRZ modulation, which still presents the lowest sensitivity from all analysed formats in BtB configuration. It is now −24.5 dBm. Moreover, for the same reason, the 20 km propagation case now presents a finite sensitivity of −22 dBm, which is found to be below the sensitivities measured for DB and PAM-4 formats for the same fibre length. The sensitivities of the latter modulation formats in BtB configuration are around −20 dBm, thus presenting an improvement with respect to the case where SOA1 is employed of 2.6 dB for DB and 1.5 dB for PAM-4. A negative power penalty of about 3 dB is also observed for these two formats in the 20 km propagation case. Furthermore, DB modulation now exhibits a finite sensitivity for the 50 km propagation case of −15.0 dBm, whereas PAM-4 presents a relevant improvement of more than 5 dB with respect to the equivalent simulations performed with SOA1.

The improvement gained by switching to the optimized SOA (instead of using SOA1) is more striking when calculating the available power budget (see Table 6). In spite of the tiny reduction in SOA output power experienced by using SOA2, now NRZ can indeed be used to implement a 10G PON since the available power budget after 20 km propagation amounts to about 40 dB. However, the more interesting improvement comes from PAM-4 modulation, where the 50 km propagation case reaches a power budget of 35.3 dB. This figure is only 41.0-35.3 = 5.7 dB shorter than the power budget required to use the discussed transmitter technology in Super-PONs. We think that this extra ~6 dB can be gained by implementing a combination of

![Figure 10](image-url)

**Figure 10** Simulated BER performance as a function of received optical power of the system shown in Figure 2 using SOA2 for 0, 20 and 50 km transmissions at 10 Gb/s with NRZ, DB and PAM-4 modulations. The LDPC-FEC BER threshold is marked with a horizontal line. BER, bit-error ratio; DB, duobinary; LDPC-FEC, low-density parity-check forward error correction; NRZ, non-return-to-zero; PAM-4, quaternary pulse amplitude modulation; SOA, semiconductor optical amplifiers.

| Table 6 | Sensitivity at BER = 1×10⁻², SOA output power and corresponding power budget for links 0, 20 and 50 km long, and for NRZ, DB and PAM-4 modulation formats. Simulations performed using SOA2 at 10 Gb/s |
|---------|------------------------------------------------|
|         | BtB | 20 km | 50 km |
| NRZ     | Sensitivity [dBm] | −24.5 | −22.0 | Floor* |
|        | SOA output power [dBm] | 18.2 | 18.2 | 18.2 |
|        | Power budget [dB] | 42.7 | 40.2 | 0 |
| DB      | Sensitivity [dBm] | −20.5 | −20.0 | −15.0 |
|        | SOA output power [dBm] | 18.1 | 18.1 | 18.1 |
|        | Power budget [dB] | 38.6 | 38.1 | 33.1 |
| PAM-4   | Sensitivity [dBm] | −20.0 | −19.8 | −17.2 |
|        | SOA output power [dBm] | 18.1 | 18.1 | 18.1 |
|        | Power budget [dB] | 38.1 | 37.9 | 35.3 |

*Floor means that, for all calculated ROP values, BER >1×10⁻². 

**Abbreviations:** BER, bit-error ratio; BtB, back-to-back; DB, duobinary; NRZ, non-return-to-zero; PAM-4, quaternary pulse amplitude modulation; SOA, semiconductor optical amplifiers.
factors: using an optimized photodetector (a sensitivity below -30 dBm is reported in [4] for 10 Gb/s NRZ transmission); increasing the SOA gain; maximizing the PAM-4 outer extinction ratio and eye opening (especially of the lower eye) by optimizing the driving electrical signal; tailoring the chirp exhibited by the waveform coming out from the SOA; and using electronic digital signal processing to compensate for fiber dispersion and other system impairments. The envisaged Super-PON transmitters would, in principle, avoid the use of EDFAs and hence represent, we believe, an alternative worth investigating.

4 | CONCLUSION

We have presented a numerical analysis to compare, under very similar conditions, three of the most common IM/DD modulation formats when used to directly modulate a semiconductor optical amplifier. Both, BtB and fibre transmission configurations were considered. We found that, in agreement with a preliminary bandwidth analysis, PAM-4 outperforms DB and NRZ modulation formats in terms of achievable modulation speed when measured at the LDPC-BER threshold of $1 \times 10^{-2}$. The advantage is preserved even after 20 km transmission in C-band. Our analysis also demonstrates that for an optimized SOA and under favourable operation conditions, the amplifier can be modulated up to 29 Gb/s with PAM-4 signalling in BtB configuration, thus representing an almost 4 Gb/s extension with respect to the case where NRZ is employed. Higher modulation speeds can be achieved by driving the SOA deeper into saturation at the expense of amplifier gain. Unfortunately, the achievable operational bit rate becomes severely degraded due to fibre chromatic dispersion, thus preventing the use of the analysed SOA-based transmitters in short-reach 25G systems operating in C-band. They could be employed, nonetheless, as 10G PON transmitters since an output power as high as 18 dBm was numerically demonstrated for the analysed device. A more appealing application is Super-PONs because of its recent introduction and chance for improvement. According to our analysis, a 10 Gb/s PAM-4 sensitivity at BtB of $-20$ dBm plus a 50 km transmission power penalty of less than 3 dB can be achieved. The available corresponding power budget for the 50 km case then becomes 35 dB, which is only 6 dB shorter than the one currently stated by the Task Force working on the Super-PON design (i.e. 41 dB). We are confident that this ~6 dB could be bridged through a combination of novel techniques such as driving waveform optimization via digital signal processing, thus motivating further research in this direction [31].

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ORCID
Ramón Gutiérrez-Castrejón ⋆ https://orcid.org/0000-0002-0380-7745
Pablo Torres-Ferrera ⋆ https://orcid.org/0000-0001-9374-4938

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