



Performance Comparisons Between the Semiconductor Optical Amplifier (SOA) and the Erbium-Doped Fiber Amplifier (EDFA)

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Abstract

This study provides a comprehensive comparison between erbium-doped fiber amplifiers (EDFAs) and semiconductor optical amplifiers (SOAs), focusing on their potential suitability for long-haul optical transmission. Using identical configurations and data rates in OptiSystem simulations, performance metrics such as gain, Q-factor, and signal-to-noise ratio (SNR) were systematically analyzed over a wide span of input powers. Saturation analysis revealed that SOAs can achieve comparable or even superior gain to EDFAs under certain operating points. The results indicate that SOAs deliver significantly higher Q-factors before deep saturation occurs, with observed improvements of up to 25 dB at an input level of 11.9 dBm. Similarly, the SNR of SOAs exceeded that of EDFAs by nearly 20 dB under identical conditions. These findings suggest that, when biased in the appropriate regime, SOAs hold strong potential for deployment in next-generation long-haul optical systems.

Keywords: Semiconductor Optical Amplifier (SOA), Erbium-Doped-Fiber-Amplifier (EDFA), Q-factor

Received: September 05th, 2025 / Revised: October 13th, 2025 / Accepted: October 27th, 2025 / Online: November 04th, 2025

I. INTRODUCTION

The semiconductor optical amplifier (SOA) and erbium-doped fiber amplifier (EDFA) have been extensively compared in literature [1–4]. EDFAs dominate current optical transmission networks as booster and inline amplifiers, owing to their broad gain spectrum, low noise figure, and ability to amplify multiple wavelength channels simultaneously [5]. In contrast, SOAs are compact and integrable but typically deliver lower amplification than EDFAs [6]. Their primary deployment has been in shorter links, such as metropolitan networks. However, SOAs possess a diverse set of nonlinear functions not achievable with EDFAs, making them attractive for advanced photonic processing

applications [7, 8]. Despite this, EDFAs remain the amplifier of choice for most existing systems [6].

Beyond their nonlinear response, SOAs also demonstrate effective suppression of intensity noise, as highlighted by several recent works [9–12]. Operating SOAs in deep saturation enhances their power efficiency and noise-suppressing behavior, though this requires sufficiently strong input signals. This study investigates these characteristics in detail to assess the viability of SOAs for long-haul communication. The novelty lies in extending the analysis into the deep saturation region (8–15 dBm), comparing both amplifier types under matched simulation conditions. Metrics such as gain, Q-factor, and SNR were systematically examined to establish a fair comparison.

The rest of this paper is structured as follows: Section 2 details the simulation set-up, Section 3 presents and analyzes the results, and Section 4 concludes with key findings.

II. EXPERIMENTAL SYSTEM

The system simulations were conducted in OptiSystem, a flexible design platform for optical networks that integrates transmitter, receiver, filtering, and amplifier models. This allowed controlled evaluation of SOAs and EDFAs under identical operating conditions. Figure 1 illustrates the configuration. A 1552 nm modulated input signal at 10 Gb/s was directed into both amplifiers. Three optical attenuators were employed to vary input powers and emulate fiber propagation. Q-factors were measured using preset Bessel filters (20 GHz, centered at 1552 nm), while two demultiplexers ensured signals were equally split for parallel comparison. SOA bias was fixed at 1 A for all measurements.

Tables I and II summarize the default OptiSystem parameters for the SOA and EDFA, respectively. These values were held constant throughout the analysis to maintain consistency.

TABLE I. SOA PARAMETERS

Name	Value	Units	Mode
Length	5.00E-06	m	Normal
Width	3.00E-06	m	Normal
Height	8.00E-08	m	Normal
Optical confinement factor	0.3		Normal
Loss	0	1/m	Normal
Differential gain	2.78E-20	m ²	Normal
Carrier density at transparency	1.40E+24	m ⁻³	Normal
Linewidth enhancement factor	5		Normal
Recombination coefficient A	1.43E+08	1/s	Normal
Recombination coefficient B	1.00E-16	m ³ /s	Normal
Recombination coefficient C	3.00E-41	m ⁶ /s	Normal
Initial carrier density	3.00E+24	m ⁻³	Normal

TABLE II. EDFA PARAMETERS

Name	Value	Units
Core radius	2.2	μm
Er doping radius	2.2	μm
Er metastable lifetime	10	ms
Numerical aperture	0.24	
Er ion density	1.00E+25	m ⁻³
Loss at 1550 nm	0.1	dB/m
Loss at 980 nm	0.15	dB/m
Length	5	m

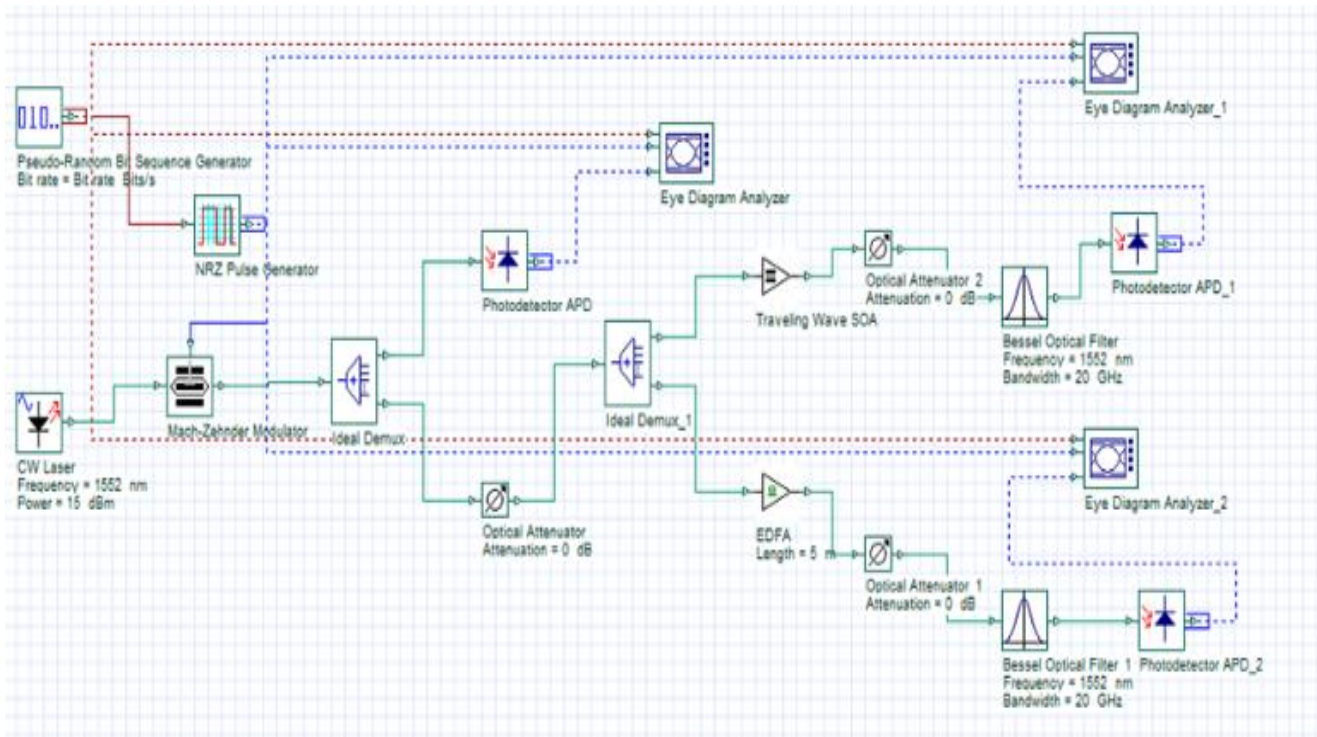


Fig. 1. Experimental Set-up

III. RESULTS

In this work, the Q-factor and signal-to-noise ratio (SNR) metrics are employed to assess system performance. The software used, OptiSystem, determines the Q-factor based on the classical definition for binary signaling, expressed as:

$$Q = |\mu_1 - \mu_0| / (\sigma_1 + \sigma_0) \quad (1)$$

where μ_1 and μ_0 represent the mean values of the received “1” and “0” levels, respectively, and σ_1 and σ_0 denote the corresponding standard deviations (noise) of the “1” and “0” levels. Both the Q-factor and SNR estimations incorporate all physical degradation factors that deteriorate the signal and ultimately determine the bit error rate (BER). A higher Q-factor or SNR corresponds to a lower BER. In this study, the Q-factor is reported in decibels (dB) as derived by the software. Similarly,

the SNR is measured in the software using an electrical analyzer, which also provides results in dB. For on-off keying (OOK) with equal noise contributions on the “1” and “0” levels, the mathematical relationship between Q-factor and SNR is typically expressed as:

$$\text{SNR} = 2Q^2 \quad (2)$$

It was first necessary to investigate the saturation characteristics of the SOA at the same wavelength used in the experiments (1552 nm). Figure 2 shows the result of varying the input power for the change in output power for the SOA. The trend obtained is very characteristic, with a third order polynomial fit given to the data, and gives us a good initial idea of the best input for conceptual noise suppression, as shown in Figure 3 (between 0 and about 15 dBm). The R correlation fit value here was 0.9991, indicating a high level of confidence.

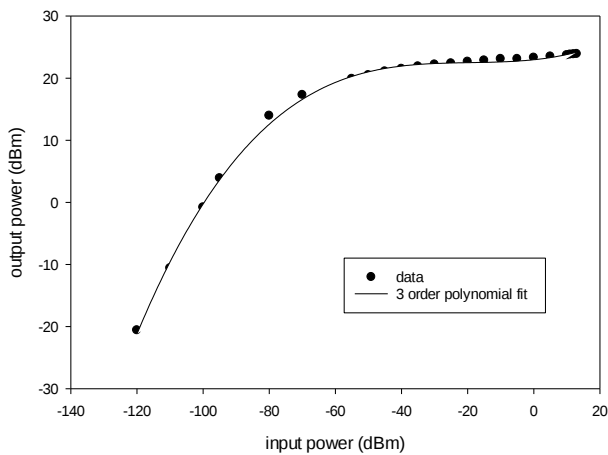


Fig. 2. SOA output power (dBm) vs. input power (dBm)

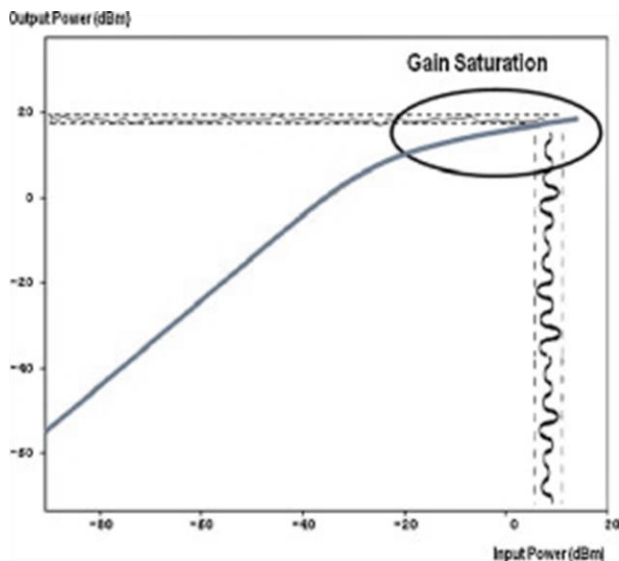


Fig. 3. conceptual SOA noise suppression (8)

Figure 3 shows how the SOA noise suppression works from the literature [8]. By virtue of the non-linear slope of the curve in the saturation region, the output from the input is

effectively “squashed”, which means the intensity noise reduces. Figure 4 shows the results of saturation input power investigation into the SOA used. The characteristic trend obtained, very similar to the literature [8] and with a third order polynomial fit given to the data, showed us that the SOA is operating in deep saturation between 0 and about 15 dBm. Therefore, we would expect the best noise reduction in this region. The R correlation fit value here was 0.9999, indicating a high level of confidence.

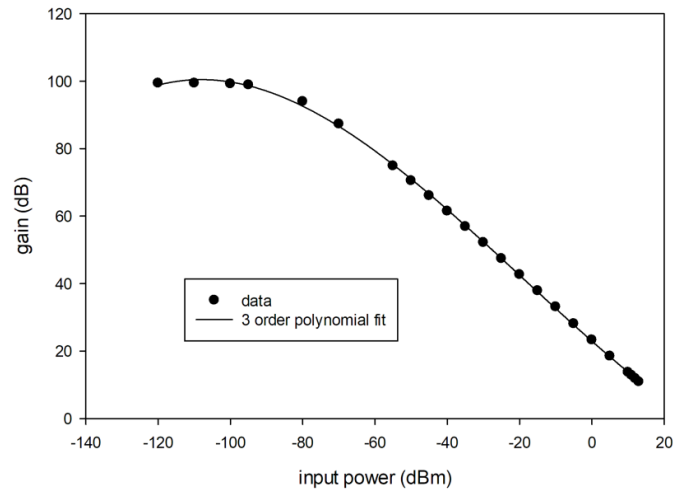


Fig. 4. SOA saturation characteristics

We then investigated the EDFA saturation characteristics and compared them to the SOA ones shown in Figure 4. These results as shown in Figure 5. It can be seen that the EDFA has better gain at very low input powers (< about -75 dBm), but the SOA has better gain with input powers above this. A 3 O polynomial fit was again given to the data. The R correlation fit values here were 0.9999 for the SOA (from Figure 4) and 0.9996 for the EDFA, indicating high levels of confidence.

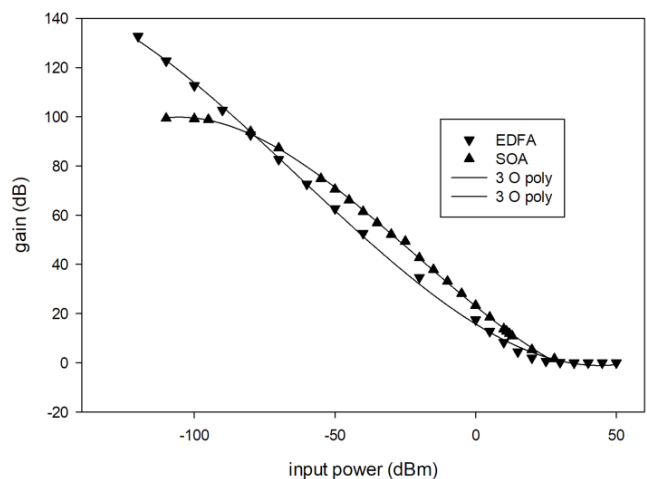


Fig. 5. EDFA vs. SOA saturation characteristics

After the saturation characteristics of both amplifiers were determined, we began to investigate both amplifier performances at various identical input powers (dBm), using *only* attenuator 0 (from Figure 1) to set the *same* power into both. The links after each amplifier to the ends of the links were *not*

attenuated. From Figure 6, the results revealed a region where the SOA out-performed the EDFA, between about 8 to 15 dBm input power. Further analyses of the results around this region shows an 8.1 dB maximum increase in Q-factor at an input of 11.9 dBm. Table III highlights these results in the SOA saturation region.

TABLE III. Q-FACTOR IMPROVEMENTS IN THE SOA SATURATION REGION

Input Power to both amplifiers (dBm)	Q-factor SOA (dB)	Q-factor EDFA (dB)	Q-factor improvement for SOA (dB)
9.4	363.4	360.0	3.4
10	367.7	362.5	5.2
10.9	374.7	367.0	7.7
11.9	379.6	371.5	8.1
12.9	382.3	376.0	6.3
13.9	386.2	380.5	5.7
14.9	387.4	385.0	2.4

The Q-factor improvement for the SOA in Table III was calculated from the difference between the measured values in dB. It can be seen that after about 15 dBm input power, the SOA is too heavily saturated and the Q-factor measured from the SOA is seen to degrade, as shown in Figure 6.

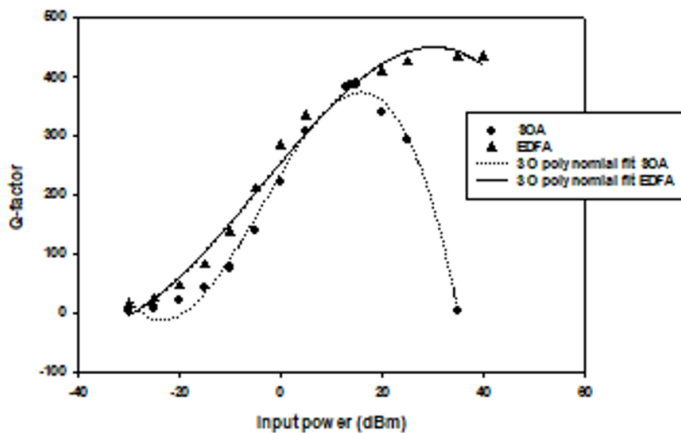


Fig. 6. Q-factor (dB) of SOA vs. Q-factor of EDFA (dB) at various input powers (dBm)

We then complemented Figure 6 by measuring the SNR of the received signal under the same conditions at the same input powers. The data received showed us that the measured SNR was always higher for the SOA, with a general improvement of about 5 dB across the input power range - except at the very high input power levels where the SOA starts to really saturate and approach those levels of the EDFA. These results are shown in Figure 7.

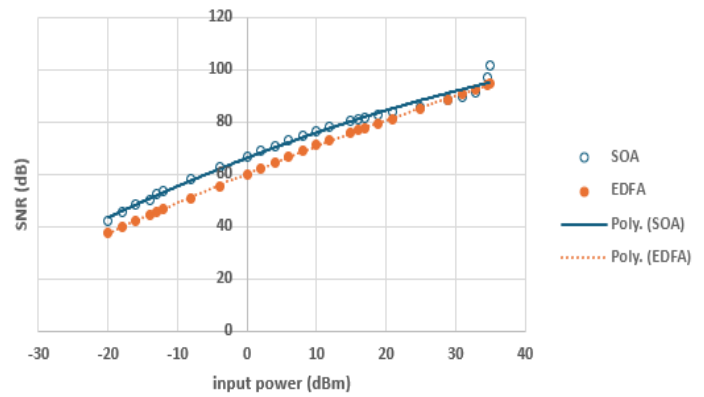


Fig. 7. SNRs vs. input powers

We then investigated the SNR vs. received power ($P_{r/x}$ dBm) measured at the *end* of both links for each amp. This was achieved using attenuators 1 and 2, as shown in Figure 1. The results are shown in Figure 8. A 4th order polynomial fit was given to each plot. The results show the superiority of the SOA in almost all cases, with maximum increases being around 20 dB at the higher received powers. At the very lowest received powers, the two curves meet. We can infer then that the SNR increases faster for the SOA than the EDFA, up to maximum received power.

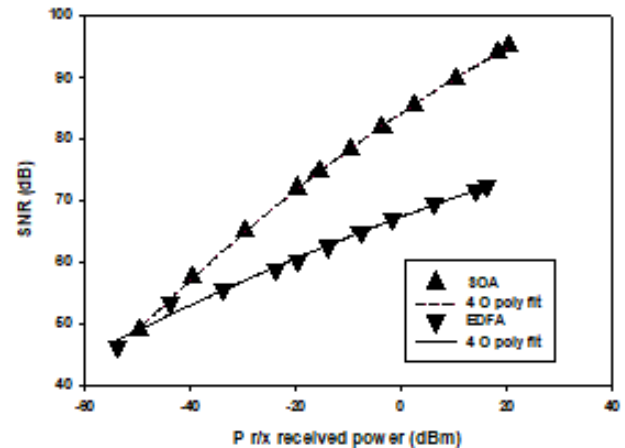


Fig. 8. SNR vs. received power ($P_{r/x}$ dBm) for both amplifiers

Figure 9 shows the eye diagrams received at 11.9 dBm input powers for both amplifiers, *without* attenuating the links. This was the same measurement point as Figure 6. The Q-factors measured were 380 and 372, respectively. This showed a maximum improvement of around 8 dB for the SOA, as shown in Table III and Figure 6.

Finally, we measured the Q-factor vs. attenuation of the final output signal for both links after the SOA and EDFA, with each amplifier having exactly the same 11.9 dBm input power (i.e. the best input power from Table III for Q-factor improvement for the SOA). The results are shown in Figure 10. The Q-factor for the SOA was seen to be better in all cases for the final signal, the maximum increase being around 25.2 dB at an attenuation of 10 dB for both. This corresponded to received powers ($P_{r/x}$) of 10.6 dBm and 8.6 dBm for the SOA and the EDFA, respectively. The increase in the SNR of the SOA over the

EDFA was around 20 dB under exactly the same conditions, as shown in Figure 8.

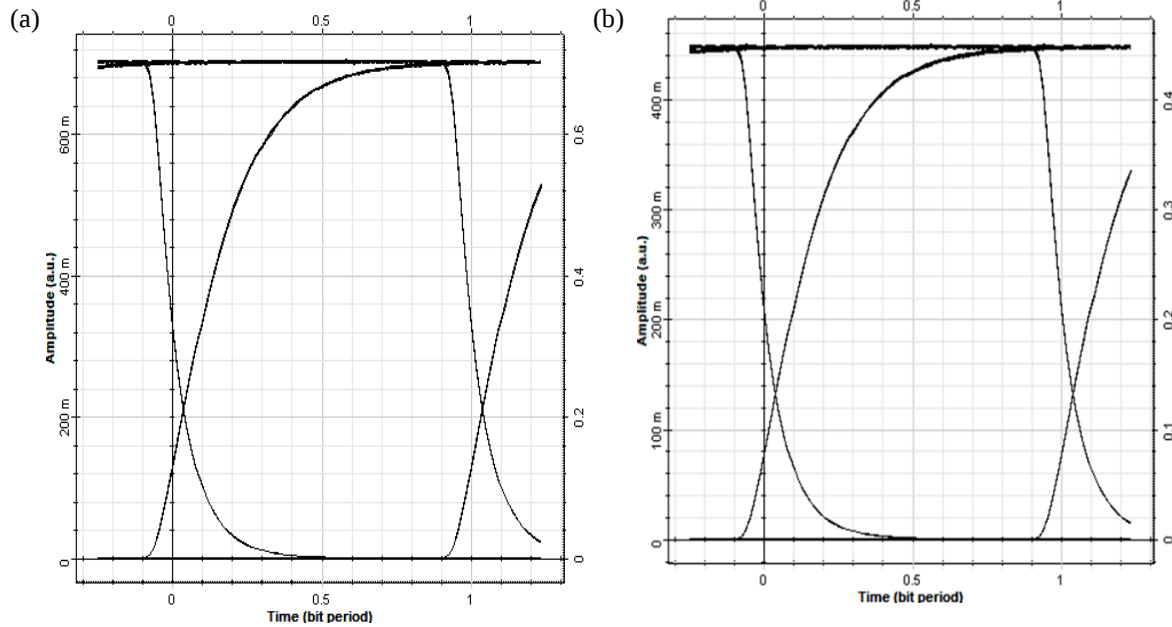


Fig. 9. Received eye diagrams at 11.9 dBm input powers for a) SOA b) EDFA

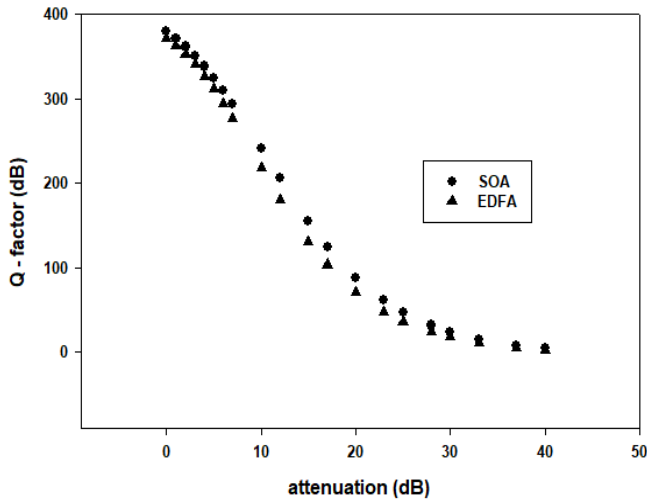


Fig. 10. Q-factor of final signal vs. attenuation of SOA and EDFA at 11.9 dBm input power to both amplifiers

IV. CONCLUSIONS

In this study, we have conducted a direct comparative evaluation of EDFA and SOA amplifiers under identical conditions. From saturation measurements obtained on both devices, our results show that the gain of the SOA is comparable to the EDFA and even better under certain conditions – at the same 10Gb/s bit rate and 1552 nm wavelength. Also, when operated in a certain saturation regime (input power ≈ 11.9 dBm), the SOA delivers markedly superior performance: with up to 25.2 dB improvement in the measured Q-factor of the final signal output relative to the EDFA, and around 20 dB improvement in the measured SNR under exactly the same conditions. This challenges the traditional view that SOAs are suitable only for short-reach applications, instead suggesting

their potential as viable alternatives in certain long-haul scenarios. Despite the limitations of the software, the theoretical results obtained beforehand could also aid designers of future optical links in anticipation of practical construction.

The novelty of our approach lies in:

- Employing identical operating conditions for both devices to ensure fair comparison.
- Extending the analysis into the deep saturation regime, which has been less explored in earlier studies.
- Demonstrating practical design implications: SOAs can be deliberately biased into saturation to maximize both gain efficiency and noise suppression.

These findings open a pathway for SOAs to be reconsidered for deployment in backbone networks, especially in systems requiring compact, integrable amplification with enhanced Q-factor performance. Future work could extend this analysis to more wavelengths across the full C-band (1530–1565 nm), and at multiple data rates and link lengths, to establish comprehensive design guidelines for SOA integration into next-generation optical networks. Finally, the results will shed light on conventional views that SOAs are typically more compact, integrable with photonic circuits and lower in cost but suffer from higher noise and polarization sensitivity, while EDFAs offer superior performance with lower noise and higher output power but are bulkier, more expensive, and consume more power.

ACKNOWLEDGMENT

Special thanks to the Photonics Engineering (PERG) research group at UTeM, Melaka, Malaysia for the use of their simulation software.

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