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Research Article

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Quantitative Device-to-System Analysis of Reflective Semiconductor Optical Amplifiers for Bidirectional WDM-PONs

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1. Abstract

Reflective semiconductor optical amplifiers (RSOAs) provide a small solution for amplification and remodulation in wavelength-division-multiplexed passive optical networks (WDM-PONs). But the system performance is directly affected by the device-level features of RSOAs. In this study, a quantitative device-to-system analysis of an RSOA-based bidirectional WDM-PON is shown, by coupling carrier-dependent material-gain modeling in MATLAB with a 10 Gb/s, 20 km OptiSystem transmission model. Effects of active area length and output facet reflectivity as well as gain compression and amplified spontaneous emission (ASE) behavior are studied. Calculated material-gain spectra reveal that their highest responsiveness is around the 1.55 μm operational window. The computed output power for the active-region-length range under investigation is from -29.123 dBm to 16.965 dBm and simulated gain-compression and ASE for 500 μm and 700 μm active region are presented. As an example, the predicted output power decreases from ~ 6.4 dBm to -3.8 dBm by increasing the output-facet reflectivity from 0.3 to 0.9. At the system level, the device conditions allow for 10 Gb/s transmission over 20 km of typical single mode fiber, with a simulated Q-factor of 8.78 and a matching BER of 7.38×10^{-19} . The results provide a quantitative relation between the RSOA device parameters and the bidirectional WDM-PON transmission performance as a basis for potential joint device and system level modification.

Keywords—*Reflective Semiconductor Optical Amplifier (RSOA), Passive Optical Network (PON), WDM-PON, gain saturation, amplified spontaneous emission (ASE), bidirectional optical communication, optical access networks, device-to-system analysis.*

2. Introduction

The reflective semiconductor optical amplifier (RSOA) has been widely investigated as a gain and remodulation device for the wavelength division multiplexed passive optical network (WDM-PON). Their reflecting design allows an optical carrier arriving at an optical network unit (ONU) to be amplified and modulated for the reverse path, thus reducing the requirement for a different wavelength-specific upstream transmitter. Preliminary bidirectional WDM-PON with gain saturated RSOA We have demonstrated downstream and upstream transmission rates of Gb/s over a distance of km with saturated gain above dB and input saturation power below dBm [9]. The result revealed the basic practicality of the RSOA remodulation, but also pointed up the need to take into account the gain saturation in the return path using the same device.

Further work has increased the possible data rate or expanded the range utilizing a variety of modulation and optical processing techniques. Hu et al. demonstrated an upstream transmission rate of 5.35 Gb/s across 20 km with an uncoded bit error rate $< 10^{-3}$ by using an RSOA with a bandwidth of around 1.4 GHz [1]. The connection between effective range and modulation type and RSOA bandwidth has been demonstrated by Yeh et al. who have tested 2.5 Gb/s OOK and 10 Gb/s OFDM-QAM transmission over 20, 50 and 75 km lines [11]. Parolari et al. have demonstrated 10 Gb/s full-duplex transmission with an amplified self-seeding WDM-PON transmitter based on an RSOA [2]. A colorless RSOA transmitter with high PDG up to 10.7 Gb/s was shown by Marazzi et al. [31].

We have also explored the bandwidth enhancement in the case outside the semiconductor structure. Zhang et al. presented an uplink bandwidth enhancement of about 0.15–0.3 GHz and a power-budget

enhancement of 12–17 dB with optical filtering aided by EDFA and SOA. [25] Bindhaiq et al. demonstrated a symmetric 40-Gb/s TWDM-PON across 40 km with a 32-way splitter; the downstream and upstream receiver sensitivities were approximately –22.78 and –22.71 dBm at a BER of 10^{–6} [29]. These results are useful reference points for the current 10 Gb/s, 20 km simulation, but not direct, equivalent comparisons because of differences in the designs, modulation schemes and reception conditions.

The performance of RSOA device level is limited by nonlinear gain compression, carrier dynamics and improved spontaneous emission. Guo et al explored the nonlinear effects in RSOA based OFDM-PON [6]. Antonelli and Mecozzi [8,23] obtained simplified models of the nonlinear response and modulation features of RSOA. The relevance of the spatial and temporal evolution of the optical field was demonstrated also in Connolly's pulse-propagation model of the reflection amplifier [24]. These studies show device performance before the system level studies of a Bit Error Rate or Q-factor.

The objective of this effort is to unify these two levels in a single numerical method. Semiconductor analysis provides trends in gain and device parameters. Then the selected device conditions are included in a bidirectional PON simulation with the communication model. The contribution is thus the quantitative coupling of active-region length, facet reflectivity, gain and ASE behavior and the resultant optical transmission metrics.

2.1 Material-gain relation

The semiconductor computation employs the carrier-dependent material-gain relationship outlined below. The expression is preserved from the numerical analysis to display the equation utilized in the MATLAB computation in its authentic format.

$$g_m(\nu, n) = \frac{c^2}{4\sqrt{2}\pi^3 n_r^2 \tau \nu^2} \left(\frac{2m_e m_{hh}}{\hbar(m_e + m_{hh})} \right)^{\frac{3}{2}} \sqrt{\nu - \frac{E_g(n)}{\hbar}} (f_c - f_v) \quad (1)$$

In Equation (1), $g_m(\nu, n)$ represents the material gain coefficient, ν denotes the optical frequency, n signifies carrier density, c indicates the speed of light in a vacuum, n_r refers to the refractive index of the active material, τ is the relaxation time of the valence band, m_e and m_{hh} are the effective masses of electrons and heavy holes, $\hbar$ stands for Planck's constant, $E_g(n)$ is the bandgap energy dependent on carrier density, and f_c and f_v are the occupation factors for electrons and the valence band, respectively.

3. Methodology

3.1 Simulation workflow

The research employed MATLAB for the RSOA computations and OptiSystem for the PON simulation. MATLAB was employed to compute material gain and to analyze the length of the active region and the reflectivity of the output facet. The chosen parameters were subsequently employed in OptiSystem to derive output power, optical spectrum, eye diagram, Q-factor, and BER.

- Semiconductor material-gain calculation in MATLAB.
- Active-region-length and output-facet-reflectivity sweeps.
- Implementation of the bidirectional PON in OptiSystem.
- Evaluation of output power, optical spectrum, eye diagram, Q-factor and BER.

3.2 Bidirectional PON architecture

Figure 1 illustrates the bidirectional framework employed in the research. Optical circulators distinguish between the forward and return pathways, whereas the RSOA is situated at the ONU. The design illustrates RSOA-centric remodulation using a shared optical fiber route.

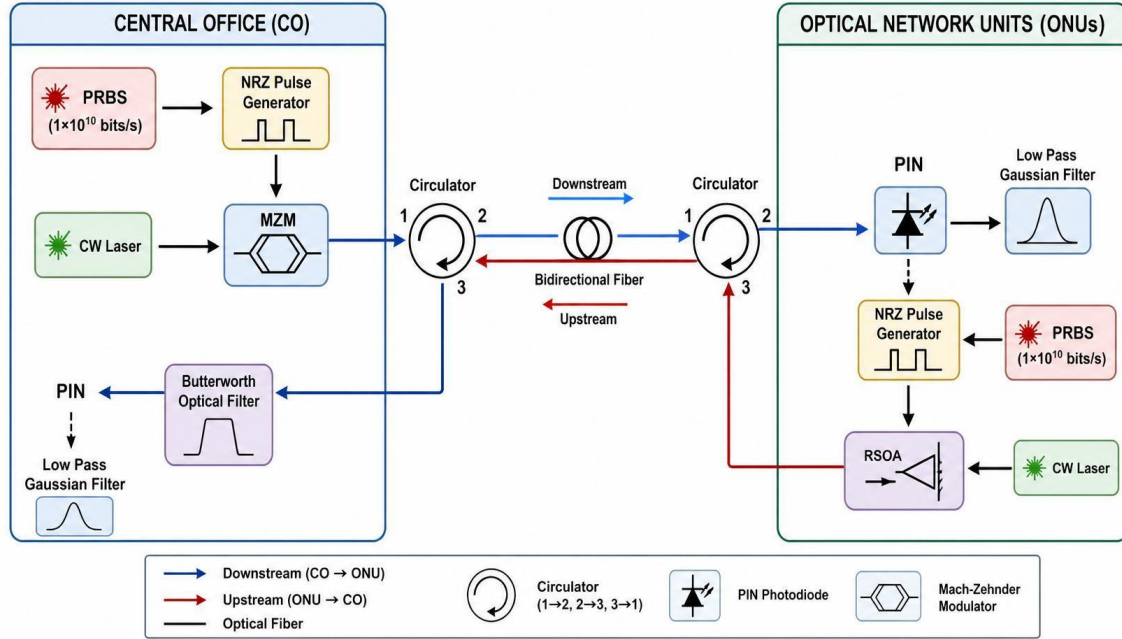


Fig. 1. Bidirectional PON architecture with RSOA at the ONU. Optical circulators separate the downstream and upstream paths.

The diagram additionally includes a local continuous wave laser at the optical network unit. Since that source is derived from the ONU, the diagram by itself does not confirm an entirely colorless ONU. The examination consequently employs the more precise term RSOA-based remodulation. A conclusive assertion on wavelength reuse necessitates the original OptiSystem source file and a spectrum where the pertinent carriers are distinctly separated.

3.3 MATLAB-based RSOA modelling

The material-gain relationship outlined in Section 2.1 was assessed for an InGaAsP active region within the 1.55 μm transmission window. The carrier density ranged from 2.0×10^{24} to $3.0 \times 10^{24} \text{ m}^{-3}$. The resultant spectra were employed to ascertain the wavelength range of peak computed material gain.

3.4 Active-region length

The computation of active length encompasses eight points ranging from $1.10 \times 10^{-8} \text{ m}$ to $1.00 \times 10^{-2} \text{ m}$. The coordinates were derived from the subsequent equation.

$$L_i = L_{\min} + \frac{i-1}{N-1} (L_{\max} - L_{\min}), \quad i = 1, 2, \dots, N \quad (2)$$

In this case, N equals 8, with $L_{\min}$ at $1.10 \times 10^{-8} \text{ meters}$ and $L_{\max}$ at $1.00 \times 10^{-2} \text{ meters}$. The research evaluated signal amplification, ASE power, output power, gain saturation, and nonlinear behavior for each aspect. The minimal numerical point is equivalent to 11 nm. It is preserved due to its association with the initial sweep, however it is not regarded as a functional RSOA geometry. The distinct simulations at 500 μm and 700 μm yield the sub-millimeter comparison.

3.5 Output-facet reflectivity

The output-facet reflectivity ranged from 0.3 to 0.9. The input facet was maintained at $R_{in} = 5 \times 10^{-5}$ throughout this sweep to ensure that variations in the computed response could be attributed to the output facet rather than concurrent alterations at both ends of the cavity.

$$R_i = R_{\min} + \frac{i-1}{N-1} (R_{\max} - R_{\min}), \quad i = 1, 2, \dots, N \quad (3)$$

where

$$R_{\min} = 0.3, \quad R_{\max} = 0.9, \quad R_{in} = 5 \times 10^{-5}.$$

Equation (3) produces the eight reflectivity measurements. This constitutes a sensitivity analysis with a single parameter instead of a simultaneous optimization of active length and reflectivity. In the computation of active length, both parameters were set at 5×10^{-5} , while the reflectivity analysis varies R_{out} between 0.3 and 0.9. A global optimum necessitates a two-dimensional length–reflectivity analysis.

3.6 ASE calculation

ASE power was evaluated with the gain-dependent expression retained from the calculation.

$$P_{ASE} = 2n_{sp}(G - 1)h\nu B \quad (4)$$

In Equation (4), P_{ASE} denotes the ASE power, n_{sp} represents the spontaneous-emission factor, G signifies linear optical gain, h refers to Planck's constant, ν indicates optical frequency, and B stands for the optical noise bandwidth. The statement clearly delineates the dependence on gain. As input power escalates into the saturation domain, G diminishes, resulting in a reduction of the gain-dependent ASE component, despite the intensification of carrier depletion and nonlinear distortion. This differentiation is crucial when analyzing the gain and ASE curves concurrently.

3.7 OptiSystem bidirectional PON model

The system architecture includes a continuous wave optical source, Mach-Zehnder modulator, 10 Gb/s non-return-to-zero data, 20 km single-mode fiber, optical circulators, 1: N splitter, RSOA-based optical network units, PIN photodetectors, optical spectrum analyzer, and bit error rate analyzer. In the long lasting model, the fiber parameters that can be observed include attenuation 0.2 dB/km and dispersion 17 ps/nm km. The downstream optical carrier is 1550 nm with an input optical power of 10 dBm.

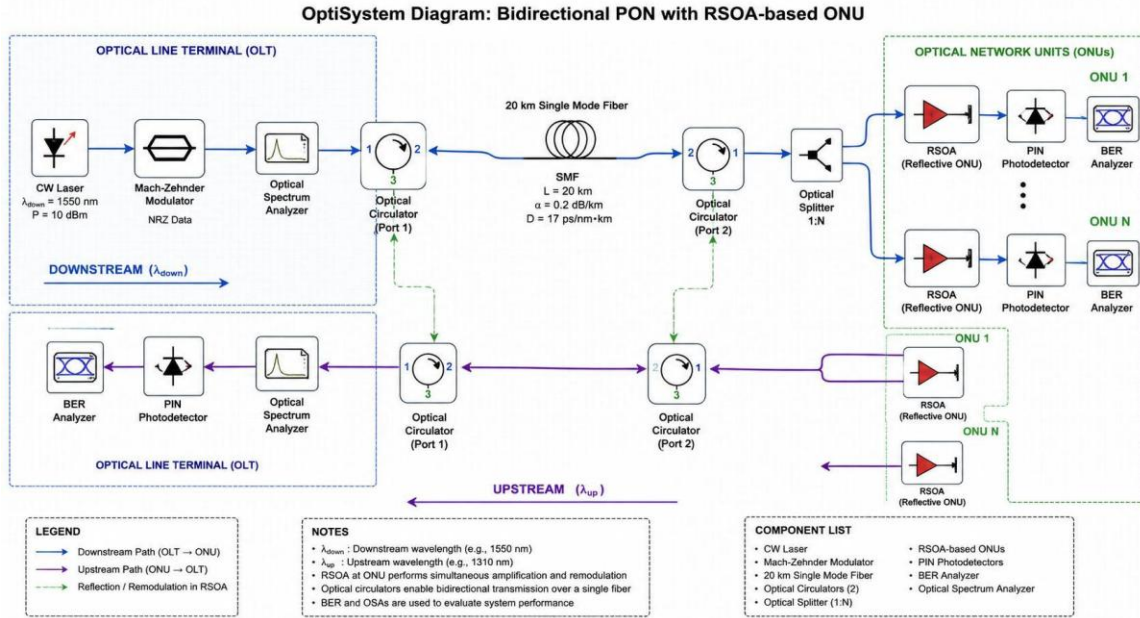


Fig. 2. OptiSystem implementation of the bidirectional WDM-PON architecture with RSOA-based ONUs, 20 km single-mode fibre and optical monitoring blocks.

The PRBS source in the initial configuration is designated as 1×10^{10} bits/s, indicating a data rate of 10 Gb/s. Parameters like RSOA bias current, internal carrier lifespan, precise splitter insertion loss, PRBS order, samples per bit, and receiver electrical bandwidth are hence not arrived at through simple conjecture.

Table I. Parameters used in the OptiSystem system simulation.

System parameter	Value recoverable from the supplied record	Source in record
Data format	NRZ	PRBS / system schematic
Bit rate	10 Gb/s	PRBS source labelled 1×10^{10} bits/s
Downstream wavelength	1550 nm	CW laser label in OptiSystem schematic
Input optical power	10 dBm	OptiSystem / active-length table
Transmission fibre	Standard single-mode fibre, 20 km	OptiSystem schematic and text
Fibre attenuation	0.2 dB/km	OptiSystem schematic
Chromatic dispersion	17 ps/nm·km	OptiSystem schematic
Splitter	1:N; N not specified	OptiSystem schematic
ONU device	RSOA	Architecture schematic
Receiver	PIN photodetector	OptiSystem schematic
Monitoring	Optical spectrum analyser and BER analyser	OptiSystem schematic
Device Material	InGaAsP active region	MATLAB modelling description
Operating wavelength region	Around 1.55 μ m	MATLAB modelling description
Carrier-density sweep	2.0×10^{24} to 3.0×10^{24} m ⁻³	MATLAB modelling description
Active-length sweep	1.10×10^{-8} to 1.00×10^{-2} m	MATLAB modelling description

Table I summarizes the main system and device parameters that control the bidirectional WDM-PON simulation. The 10-Gb/s NRZ signal is transmitted over 20 km of standard single mode fiber at 1550 nm with attenuation of 0.2 dB/km and chromatic dispersion of 17 ps/nm·km. The RSOA has an InGaAsP active area with the carrier density, active length, and output-facet reflectivity taken as device-specific parameters. These settings define the operating conditions of the next gain, output power, amplified spontaneous emission and system level analysis.

3.8 Performance metric

The acquired eye diagram facilitated the determination of the Q-factor, from which the associated BER was computed using the subsequent equation.

$$\text{BER} = \frac{1}{2} \text{erfc} \left(\frac{Q}{\sqrt{2}} \right) \quad (5)$$

In Eq. (5), $\text{erfc}(\cdot)$ is the complementary error function. The resulting BER is a simulation-derived quantity; no experimental BER measurement is claimed.

4. Results and Discussion

4.1 Material-gain characteristics

Calculated material-gain spectra for different carrier densities from 2.0×10^{24} to $3.0 \times 10^{24} \text{ m}^{-3}$ are shown in Fig. 3. The amplification increases with carrier density and the peak shifts to shorter wavelength. The peak is in the 1.5–1.55 μm region, which is the operating bandwidth for the next RSOA and PON simulations.

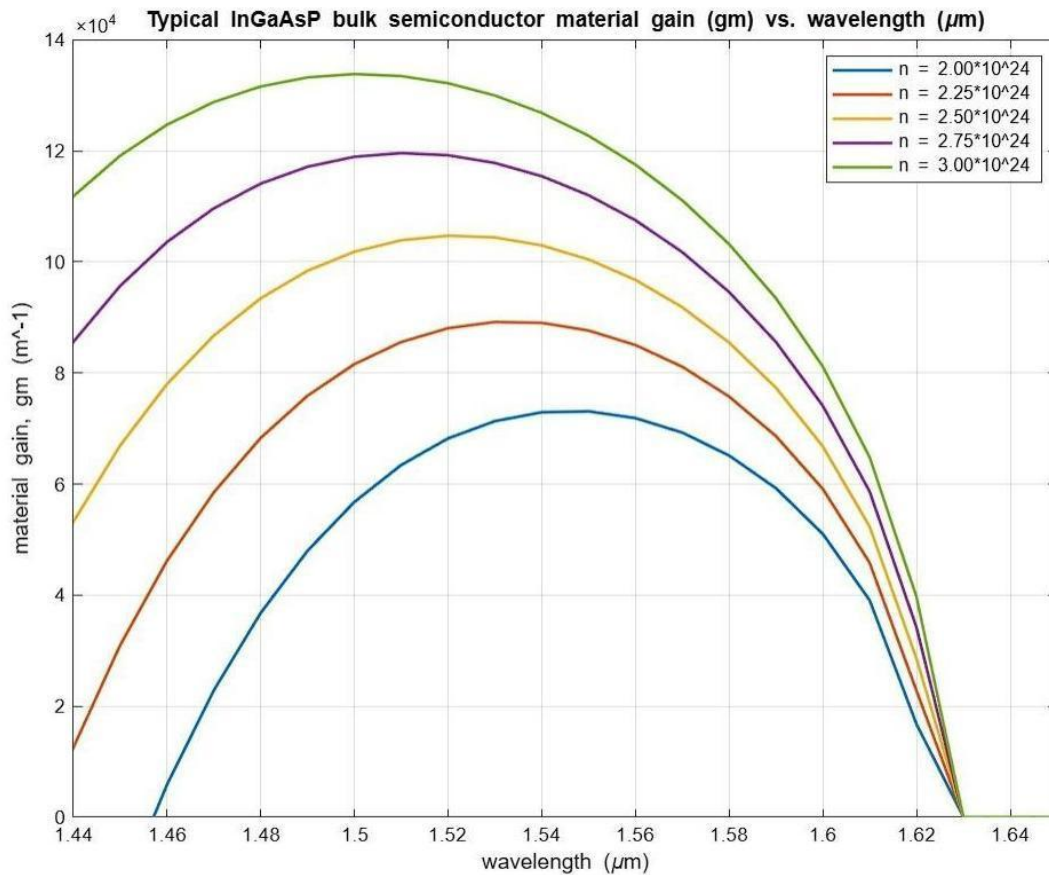


Fig. 3. MATLAB material-gain spectra of the InGaAsP active region for carrier densities between 2.0×10^{24} and $3.0 \times 10^{24} \text{ m}^{-3}$.

The calculation is consistent with the carrier-dependent gain behaviour described in analytical RSOA models [8,23,24,32].

4.2 Active-region length and output power

The effect of active-region length on the emitted optical power was studied by keeping the electrical signal and the input optical power constant at 16.324 dBm and 10 dBm, respectively. The numerical results of the first computation are presented in Table II.

Table II. Simulated output power for the original active-length sweep.

Active length (m)	Electrical signal (dBm)	Input power (dBm)	Output power (dBm)
1.00×10^{-2}	16.324	10	-29.123
0.00857143	16.324	10	-28.846
0.00714286	16.324	10	-28.484
0.00571429	16.324	10	-27.500
0.00428572	16.324	10	-14.040
0.00285715	16.324	10	-5.960
0.00142858	16.324	10	2.940
1.10×10^{-8}	16.324	10	16.965

The calculated output power as shown in Table II changes from -29.123 dBm at 1.00×10^{-2} m to 16.965 dBm at the 1.10×10^{-8} m terminal point. The 11 nm endpoint is a numerical result from the first sweep and is not a viable RSOA design.

During this period sweep, both aspects were given the same low reflectivity. Table III. shows the established facet-reflectivity setups. These configurations isolate the effect of length; nevertheless, they do not represent the cavity-feedback circumstances used later in the reflectivity analysis.

Table III. Constant RSOA facet-reflectivity parameters used for the active-length sweep.

Parameter	Value
Input facet reflectivity	5.00×10^{-5}
Output facet reflectivity	5.00×10^{-5}

In Table III, maintaining identical facet values across all lengths preserves the reflectivity condition despite variations in the active region. The independent reflectivity analysis in Section 4.3 intentionally alters the output facet. Only a single entry in Table II measures less than 1 mm, hence the length sweep alone does not substantiate a broad assertion that all sub-millimeter RSOAs are preferable.

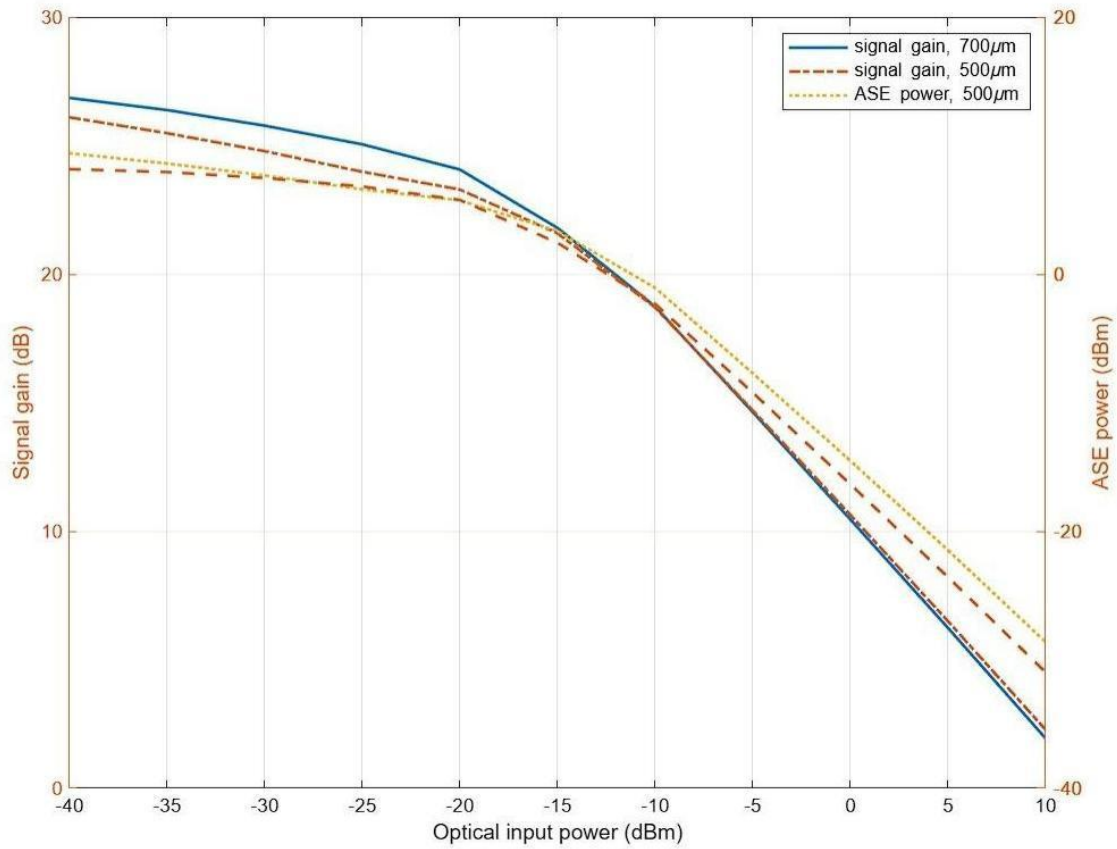


Fig. 4. Simulated signal gain and ASE power versus optical input power for 500 μm and 700 μm RSOAs.

In figure 4, the 500 μm device has a lower gain relative to the 700 μm device over the defined input-power range, but also shows less gain compression. This verifies the more precise conclusion that the active length reduction may reduce saturation in the sub-millimeter cases considered. This does not show that any RSOA that measures less than 1 mm is better.

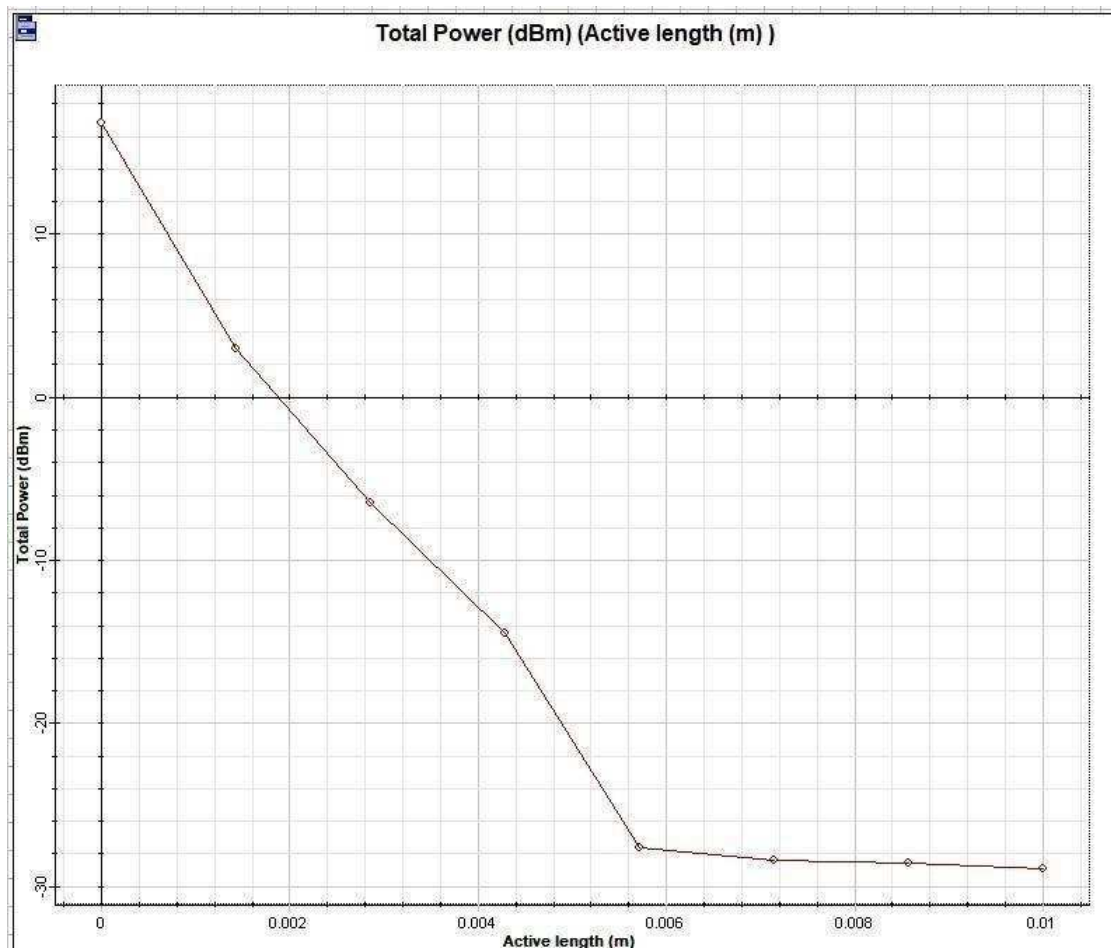


Fig. 5. Simulated output power as a function of RSOA active-region length.

The dependence of the output power of the RSOA on the length of the active region is shown in Fig. 5. As the active length increases, the output power decreases because of increased gain saturation, carrier depletion and non-linear losses. Results show that active lengths less than 1 mm give improved optical amplification by efficient carrier utilization.

4.3 Output-facet reflectivity

Figure 6 illustrates the relationship between output power and the reflectivity of the output facet. The graphed line declines from roughly 6.4 dBm at $R = 0.3$ to about -3.8 dBm at $R = 0.9$. If solely output power is utilized as the benchmark for comparison, $R = 0.3$ represents the peak output power point in the computed data.

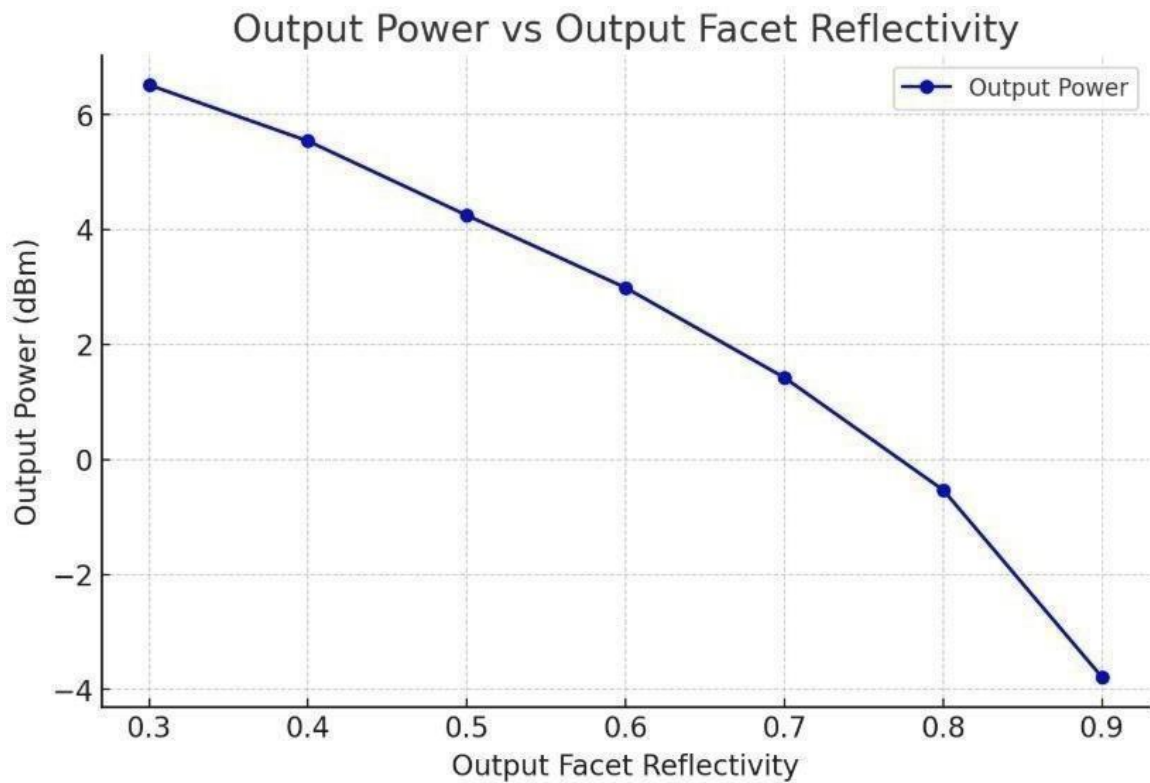


Fig. 6. Simulated output power versus output-facet reflectivity.

The ideal $R=0.4-0.5$ as previously understood does not match the shown output-power curve. The range 0.4-0.5 may also be referred to as a zone of modest feedback. To call it ideal, another criterion should be added, for example proved decrease in ASE, better BER or stability requirement, together with the required numerical analysis.

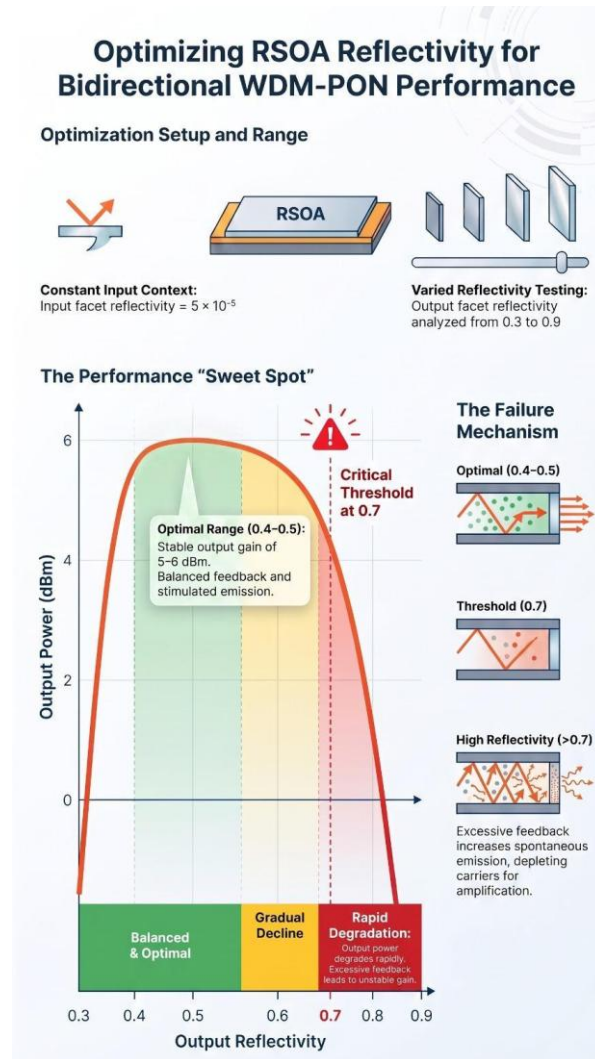


Fig. 7. Conceptual illustration of output-facet reflectivity and optical-feedback regimes in the RSOA.

The output power decreases gradually with the increase of reflectivity, and then decreases rapidly at high reflectivity values, as seen in Figure 7. The best working range is reported to be between 0.4 and 0.5, offering a stable output gain of 5 to 6 dBm [6, 24, 28].

The performance enhancement in this field arises from the synergistic combination of internal optical feedback and stimulated emission. Moderate reflectivity is sufficient for optical feedback for amplification but prevents too much cavity resonance which would lead to increased nonlinear distortion and gain saturation. Above a reflectivity of 0.7, the amplifier begins to behave erratically and the output power decreases to about -3.79 dBm for a reflectivity of 0.9. The decrease is due to the high internal reflection which results in increased spontaneous emission, increased optical feedback and finally to a decrease in the number of carriers for efficient amplification.

4.4 ASE and gain saturation

The gain curves in Figure 4 show a decay with increasing input optical power, which is the expected signature of gain compression. The ASE trace in the same graph also reduces over the input-power spectrum shown. These two observations are consistent with Equation (4) : the ASE component depends on the gain G which decreases when the RSOA approaches saturation. Therefore, the observed reduction in ASE should not be interpreted as an evidence that higher optical powers always reduce spontaneous emission, but rather as the gain-dependent metric calculated during this particular sweep.

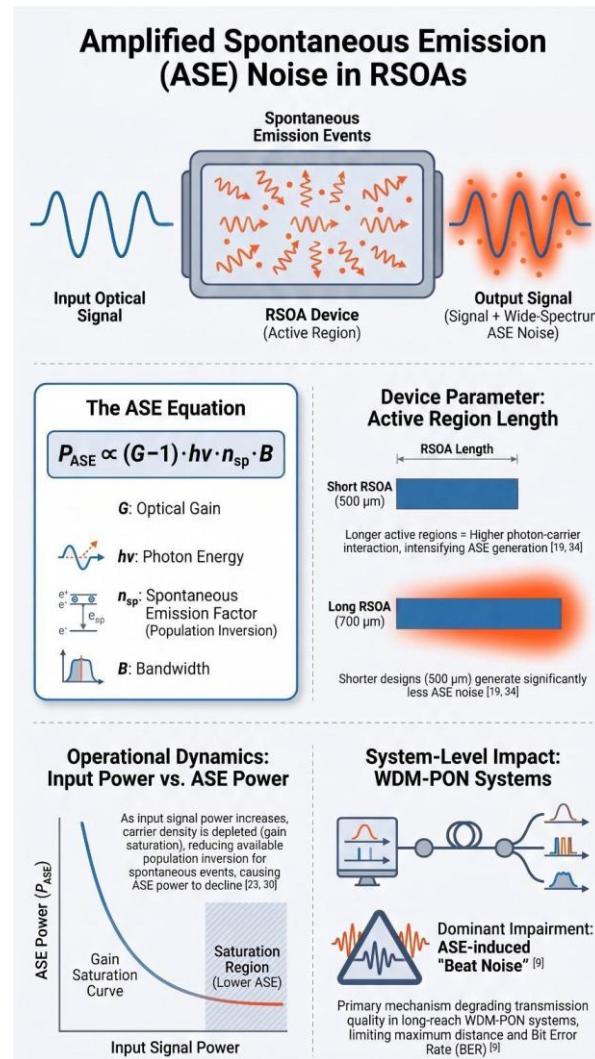


Fig. 8. Conceptual ASE-generation path and its influence on RSOA signal amplification and transmission.

Figure 8 illustrates the ASE noise generation in RSOAs and its dependence on device length and input power, and it's impact on WDM-PON transmission quality.

4.5 System-level transmission

The chosen device configurations were subsequently applied in the OptiSystem model. The system functions at a rate of 10 Gb/s across 20 kilometers of conventional single-mode fiber.

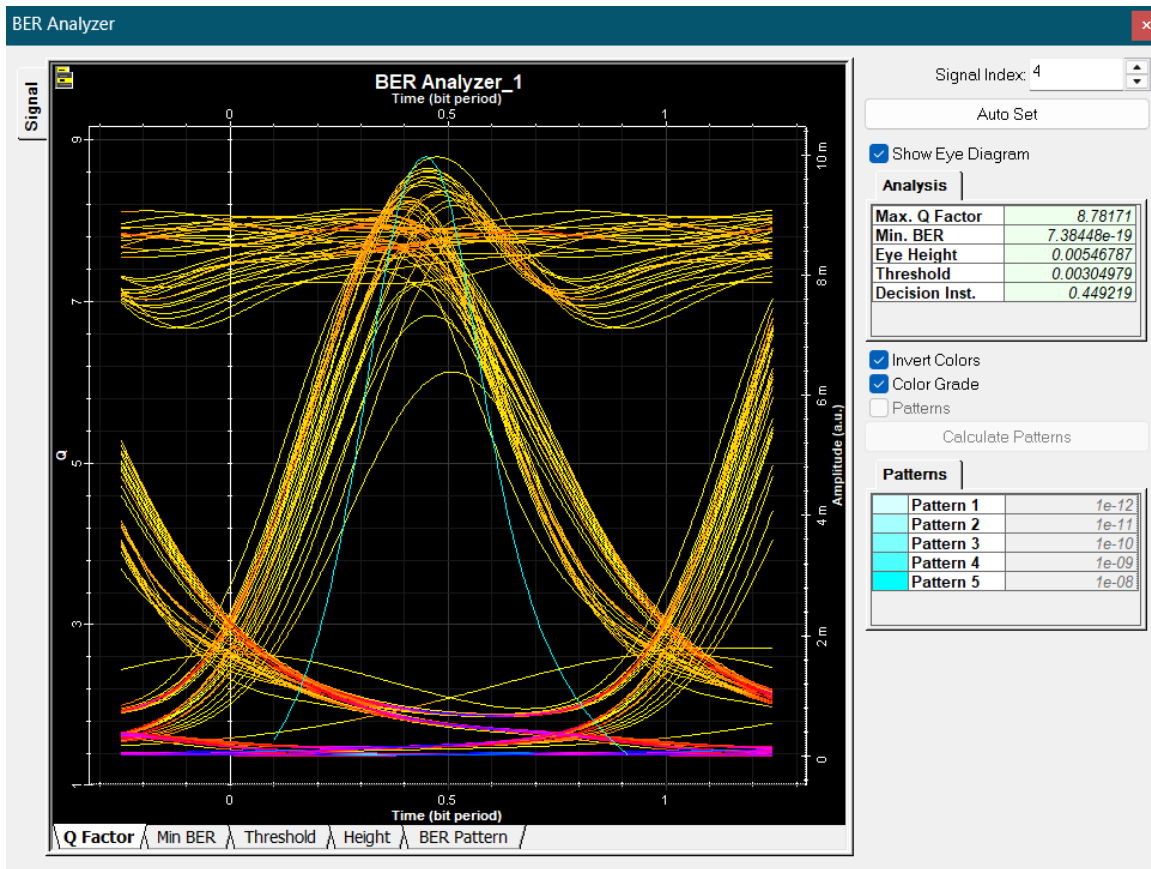


Fig. 9. Simulated upstream eye diagram with $Q = 8.78$ and $BER = 7.38 \times 10^{-19}$.

Figure 9 shows the eye diagram of the upstream signal captured from the upgraded bidirectional WDM-PON is shown in Fig. 9. The well-defined eye opening with a Q-factor of 8.78 and BER of 7.38×10^{-19} indicates low noise, negligible inter-symbol interference and high signal fidelity after 20 km transmission. The results prove that the increased RSOA active length and output facet reflectivity are effective in suppressing gain saturation and ASE degradation, thus validating the proposed device-to-system optimization for high-performance bidirectional WDM-PONs.

Fig. 10 displays the optical spectrum of the upgraded bidirectional WDM-PON. The gap between downstream and upstream carriers is 0.48 THz . The unique spectral peaks verify the successful wavelength reuse with little channel interference in a single optical connection. The BER of 7.38×10^{-19} and Q-factor of 8.78 obtained validates the effectiveness of the redesigned RSOA arrangement for improved bidirectional WDM-PON operation.

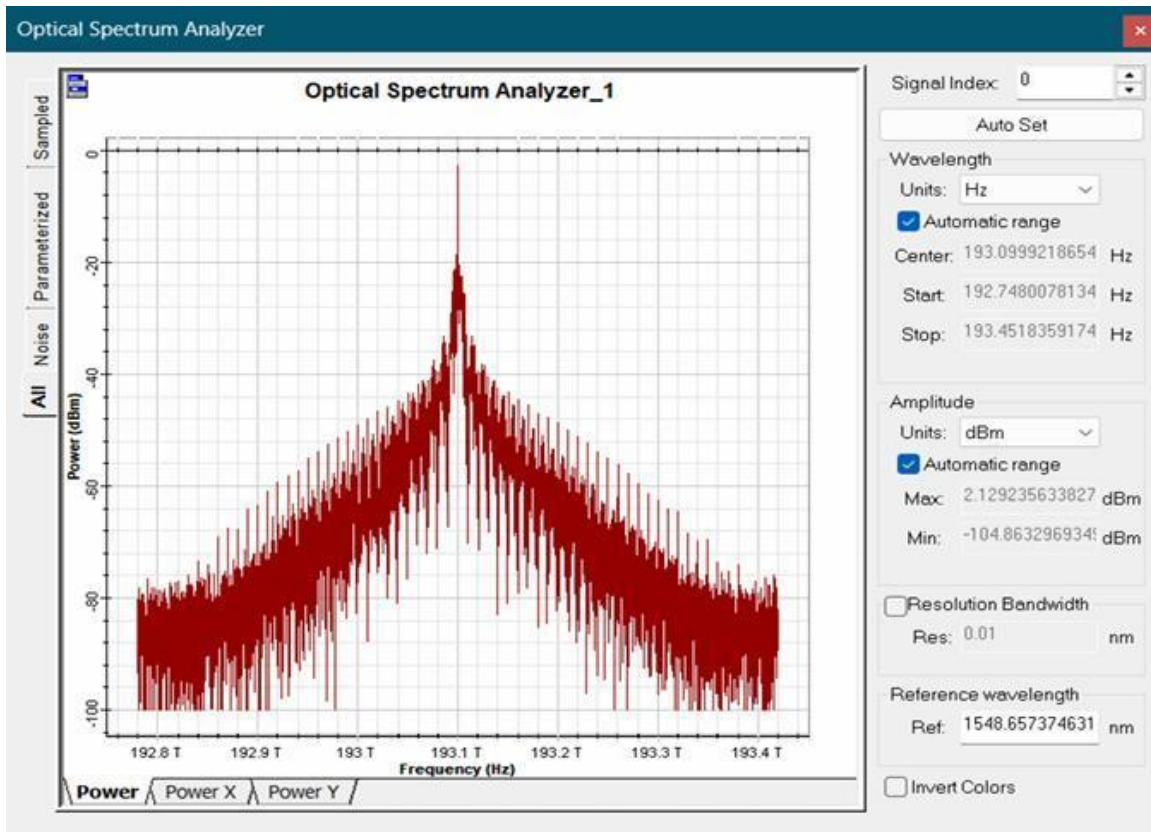


Fig. 10. Optical spectrum obtained from the simulated bidirectional system. The plotted spectrum is centred near 193.10 THz and does not independently resolve a second carrier at 193.58 THz.

4.6 Quantitative comparison with representative RSOA-PON studies

Table IV juxtaposes the current 10 Gb/s, 20 km simulation with pertinent RSOA-PON findings documented in the referenced literature. The research employs varying data rates, distances, modulation schemes, and receiver circumstances, hence the figures are provided as quantitative context instead of a straight performance hierarchy.

Table IV. Quantitative context for the present RSOA-based PON simulation.

Study	Data rate	Reach	Reported quantitative result	Context
Lee et al. [9]	2.5 Gb/s DS; 1.25 Gb/s US	20 km	Saturated gain > 13 dB; input saturation power < -13 dBm	Gain-saturated RSOA WDM-PON
Hu et al. [1]	5.35 Gb/s US	20 km	Uncoded BER < 10^{-3} ; RSOA bandwidth $\approx$ 1.4 GHz	Seeded RSOA upstream
Marazzi et al. [31]	Up to 10.7 Gb/s	Not stated	Up to 10.7-Gb/s colourless transmission	High-PDG RSOA transmitter
Bindhaiq et al. [29]	40 Gb/s	40 km	32-way split; sensitivity $\approx$ -22.78 dBm DS and -22.71 dBm US at BER = 10^{-6}	TWDM-PON with delay interferometer
Present study	10 Gb/s	20 km	Q = 8.78; BER = 7.38×10^{-19} ; output-power sweep -29.123 to 16.965 dBm	MATLAB device analysis + OptiSystem PON

Analysis shows that the existing research is within the data-rate and distance range previously defined for RSOA-based access networks. The special thing is the explicit link between the device and the system in the numerical workflow, not a claim about how far it can transmit or how fast data rates can be.

5. Conclusion and Future Work

The computations done in MATLAB and OptiSystem show the effect of the RSOA parameters on the performance of the device and the system. The gain estimation for InGaAsP material suggests that the maximum gain occurs approximately 1.55 μm in the carrier-density range studied. The computation of the active length, the output power varies between -29.123 dBm for 1.00×10^{-2} m and 16.965 dBm for 1.10×10^{-8} m. The number 11 nm is kept in the range of numbers, but it is not proposed as a possible device length.

The calculations at 500 μm and 700 μm show the effect of active length on gain compression and enhanced spontaneous emission along the range of input powers plotted. The reflectivity measurement shows a decrease in output power from around 6.4 dBm at $R = 0.3$ to around -3.8 dBm at $R = 0.9$. Therefore, in the above calculation $R = 0.3$ is the maximum output power point. To determine the best performances of the gadget, it is necessary to evaluate the length and the reflectivity simultaneously, considering both parameters.

The OptiSystem framework at the system level employs 10 Gb/s NRZ data, and 20 km of traditional single-mode fiber. The eye diagram results in a Q factor of 8.78 and a simulated Bit Error Rate of 7.38×10^{-19} . These are results from simulations, not real data. At both 193.10 and 193.58 THz, the different peaks are not clearly separated in the optical spectrum so the spectrum alone is not taken as evidence of wavelength reuse.

A more promising next step is to do a more complete active-length sweep over physically realistic RSOA dimensions and then do a two-dimensional length-reflectivity study. The research should include output power, gain, ASE, Q-factor and BER on a common parameter grid. Re-running the OptiSystem model from the original project file would allow the missing bias, carrier-lifetime, splitter, sampling and receiver parameters to be reported directly. Additional experimental measurements of gain, saturation power, and enhanced spontaneous emission, which are not available in the present simulation data, would provide verification at the device level.

Data availability statement

The data used to support the findings of this study are included within the article or are available from the corresponding author upon request.

Author contributions

Nandini Chakraborty has prepared the manuscript and contributed to the simulation of the mentioned parameters. Author has reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

Not applicable.

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