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GAIN-SATURATED SEMICONDUCTOR OPTICAL AMPLIFIERS FOR FREE-SPACE OPTICAL COMMUNICATION: PERFORMANCE LIMITATIONS AND NUMERICAL ANALYSIS OF SCINTILLATION MITIGATION

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ABSTRACT
Free-space optical (FSO) communication offers high bandwidth and security but faces reliability challenges from atmospheric turbulence and scintillation. Semiconductor optical amplifiers (SOAs) can provide simultaneous amplification and scintillation mitigation through gain saturation. This paper analyzes the physical mechanisms that are governing SOA behavior, including carrier dynamics, gain saturation, and amplified spontaneous emission. A numerical analysis is performed to quantify the trade-off between scintillation mitigation and extinction ratio degradation. Results show that a gain-saturated SOA reduces the scintillation index by 64% while introducing a 3.5 dB extinction ratio penalty. This trade-off defines the fundamental design boundary for SOA-based FSO links.

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Keywords:
Semiconductor optical amplifier; Free-space optical communication; Atmospheric turbulence; Gain saturation; Scintillation mitigation; Numerical modelling.

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Introduction

Free-space optical (FSO) communication transmits data via modulated light beams through the atmosphere, offering bandwidth capabilities far exceeding radiofrequency (RF) systems, enhanced security through narrow beam divergence, and freedom from spectrum licensing constraints (Agrawal, 2002; Maho et al., 2025). These attributes position FSO as a compelling technology for terrestrial backhaul, satellite cross-links, and unmanned aerial vehicle (UAV) networks (Maho et al., 2025). The practical reliability of FSO links, however, is fundamentally limited by the propagation channel. Atmospheric turbulence induces random refractive-index fluctuations that cause intensity scintillation, beam wander, and phase distortion (Bandele et al., 2016; Maho et al., 2025). Scintillation produces random fluctuations in received optical power and degrades the signal to noise ratio (SNR) thereby increasing the bit error rate (BER) (Bandele et al., 2016). Characteristic of mobile systems (Maho et al., 2025), scintillation is further exacerbated by misalignment and vibration-induced pointing errors. Recent turbulence modeling, for instance the

Lognormal-Shadow Rician distribution, has been developed to characterize scintillation caused by combined effects of turbulence and generalized pointing errors (Miao et al., 2024). Furthermore, generalized pointing error models based on Beckmann distribution have been proposed to quantify the joint impact of turbulence and misalignment on system capacity (Boluda-Ruiz et al., 2017).

Optical amplification is a principal strategy for compensating channel losses and extending link range (Ab-Rahman, 2014; Agrawal, 2002). However, the choice of amplifier technology and its operating regime critically affect system performance (Ab-Rahman, 2014; Tang et al., 2023). Erbium-doped fiber amplifiers (EDFAs) offer mature, low-noise amplification but are bulky and less integrable (Ab-Rahman, 2014; Agrawal, 2002). Semiconductor optical amplifiers (SOAs) provide compact, integrable, and fast-response amplification with wide gain bandwidth, making them attractive for size-constrained platforms (Maho et al., 2025; Tang et al., 2023). However, the advantage of fast carrier dynamics becomes beneficial only when the atmospheric fluctuation timescale is slower than the SOA recovery dynamics. Therefore, the suitability of SOA-based mitigation depends strongly on channel conditions and modulation format. A recent technical review has comprehensively surveyed SOA static and dynamic parameter characterizations and their applications across packet switching, UWB systems, and OCDMA systems (Misra et al., 2024). Reflective SOAs (RSOAs) offer further architectural simplification for specific applications (D. Lee et al., 2021).

The distinctive characteristic of optical amplifiers in FSO contexts is that their behavior under gain saturation can be exploited to mitigate scintillation, not merely to amplify signals (Bandele et al., 2016; Hong et al., 2019). When an amplifier operates in saturation with sufficiently fast gain dynamics, it provides higher gain to low-power input fluctuations and lower gain to high-power fluctuations, effectively equalizing the output power (Hong et al., 2019). This dual function amplification and turbulence mitigation is unique to the FSO application and distinguishes it from conventional fiber-optic amplification (Bandele et al., 2016; Hong et al., 2019). Previous studies have extensively investigated atmospheric turbulence modelling in free-space optical communication systems and have separately analyzed semiconductor optical amplifier characteristics. However, limited attention has been given to the coupled interaction between SOA gain dynamics and turbulence-induced intensity fluctuations in FSO links. In particular, the trade-off between scintillation suppression achieved through gain saturation and the resulting signal degradation due to extinction ratio reduction remains insufficiently quantified.

Therefore, this work establishes a coupled numerical analysis framework integrating SOA gain saturation behavior with atmospheric scintillation effects. The study evaluates the fundamental trade-off between fluctuation mitigation and signal quality degradation, providing design insights for selecting appropriate SOA operating conditions in reliable FSO communication systems.

The scope describes optical amplifiers, their function in FSO systems, and the fundamental limitations to system performance. Here, an emphasis is placed on design tradeoffs currently applicable to optical amplifiers. There exist other approaches to alleviate the problems caused by intensity noise, such as aperture averaging and spatial diversity (Alimi & Monteiro, 2024). Aperture averaging relies on the use of a large receiver lens to reduce intensity noise by encompassing as large a part of the traveling optical field as possible (Alimi & Monteiro, 2024). Spatial diversity utilizes multiple apertures at either the transmitter or receiver to add more spatial degrees of freedom and help combat fading and lessen the chance of temporal blockage (Alimi & Monteiro, 2024). Hybrid RF/FSO architectures with adaptive combining are other approaches to improving reliability (Liu et al., 2023; Merrouche & Aissaoui, 2024). Literature for this review was searched for on IEEE Xplore, Optica Publishing Group and Web of Science using the keywords: ‘free-space optical,’ ‘semiconductor optical amplifier,’ ‘gain saturation,’ ‘scintillation,’ and ‘optical amplifier optimization.’ Papers published in the time range of 2000 – 2025 were reviewed with preference for recent experimental works and fundamental semiconductor physics texts.

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2. Physics of Optical Amplification

2.1 Optical Amplifier Classification

Optical amplifiers used in photonic systems can be broadly classified into three categories: semiconductor optical amplifiers (SOAs), rare-earth-doped fiber amplifiers (such as erbium-doped fiber amplifiers, EDFAs), and nonlinear optical amplifiers (including Raman and Brillouin amplifiers) (Ab-Rahman, 2014; Agrawal, 2002). In rare-earth-doped fiber amplifiers, gain is achieved through stimulated emission from excited states of dopant ions (e.g., Er^{3+}) maintained in a population inversion by optical pumping (Agrawal, 2002). Nonlinear amplifiers exploit stimulated Raman or Brillouin scattering to transfer energy from a pump beam to the signal (Agrawal, 2002). Among these, SOAs provide faster carrier dynamics and greater integration flexibility compared with conventional fiber-based amplifiers (Tang et al., 2023; Xiao & Huang, 2008; Zory, 1993).

2.2 Stimulated Emission and Population Inversion

The fundamental mechanism of optical amplification is the stimulated emission (Agrawal, 2002; Zory, 1993). In a semiconductor gain medium, electrons occupy energy states in the conduction band, while holes occupy states in the valence band (Zory, 1993). When an incident photon with energy equal to the transition energy interacts with an electron in the conduction band, it stimulates recombination of the electron-hole pair, emitting a second photon with identical energy, phase, and direction (Agrawal, 2002; Zory, 1993). This process yields net optical gain when the population inversion condition is satisfied that is, when the probability of stimulated emission exceeds that of absorption (Zory, 1993).

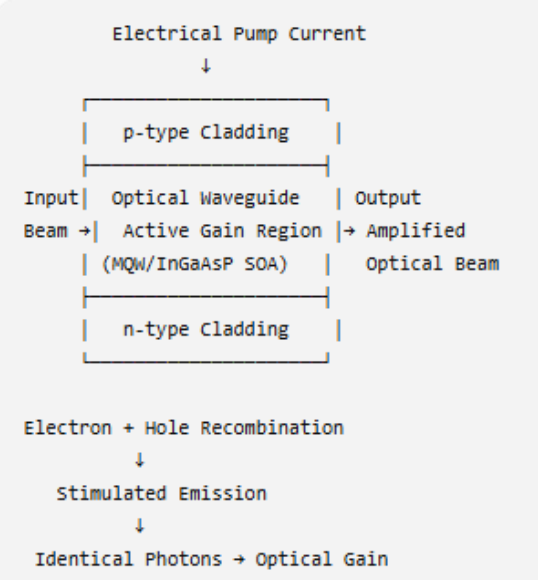


Figure 1. Schematic representation of a semiconductor optical amplifier showing carrier injection, stimulated emission and optical gain mechanism.

The SOA consists of a semiconductor active region placed between p-type and n-type cladding layers. Electrical injection creates carrier population inversion which enables stimulated emission and amplification of the incoming optical signal. The gain characteristics depend on carrier density, confinement factor and semiconductor material properties. Most semiconductor optical amplifiers are fabricated using InGaAsP and AlGaInAs structures of InP, due to their direct bandgaps and efficient radiative recombination at telecommunication wavelengths (Tang et al., 2023; Zory, 1993). Based on the material system, one can design the operating wavelength, gain bandwidth, carrier confinement, and thermal behavior of the amplifier (Zory, 1993). In direct bandgap semiconductors such as InGaAsP and AlGaInAs, the radiative recombination efficiency is high, making them suitable for optical amplification

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at telecommunication wavelengths (e.g., 1550 nm) (Tang et al., 2023; Zory, 1993). The material gain coefficient is commonly modeled as:

$$g(N) = a \cdot (N - N_0) \text{ [2,5]}$$

where a is the differential gain coefficient, N is the carrier density in the active region, and N_0 is the transparency carrier density (Zory, 1993). Gain exists only when $N > N_0$, that is, only under population inversion conditions (Xiao & Huang, 2008; Zory, 1993). In quantum well structures, the density of states becomes step-like rather than parabolic, concentrating carriers at specific energy levels. As compared to bulk material, this material modifies the gain spectrum, reduces the required transparency carrier density, and can even lessen the noise figure (Zory, 1993). There are also additional benefits for quantum dot structures. Three-dimensional carrier confinement results in delta-function-like density of states, which can lead to a lowered threshold current, reduced temperature sensitivity, and further potential for upper limits on noise figure (Xiao & Huang, 2008).

2.3 Carrier Dynamics and Gain Recovery

The dynamic response of the amplifier is determined by carrier dynamics (Tang et al., 2023; Zory, 1993). When an optical signal pulse enters the amplifier, stimulated recombination depletes the carrier population (Zory, 1993). The rate at which the carrier density recovers determines the gain recovery time τ_c, which for SOAs typically ranges from 50 to 500 ps (Tang et al., 2023; Xiao & Huang, 2008). The gain recovery time is a critical parameter for FSO applications (Hong et al., 2019). Atmospheric scintillation exhibits characteristic frequencies in the kHz to low-MHz range (Bandele et al., 2016; Maho et al., 2025). Because the SOA gain recovery time is orders of magnitude faster than scintillation fluctuations, the amplifier can track and compensate power variations essentially instantaneously (Hong et al., 2019). This time-scale separation is the fundamental enabler of saturation-based scintillation mitigation (Bandele et al., 2016; Hong et al., 2019).

2.4 Gain Saturation

Gain saturation arises when optical power in the amplifier is sufficiently high that stimulated recombination depletes the carrier population faster than the drive current can replenish it (Ab-Rahman, 2014; Li & Park, 2006). As input power increases, gain decreases from its small-signal value (Ab-Rahman, 2014). The saturation output power P_{sat} is defined as the output power at which gain compresses by 3 dB (Ab-Rahman, 2014).

$$P_{\text{sat}} = \left(\frac{h\nu}{\tau_c}\right)\left(\frac{wd}{\Gamma a}\right) \text{ (Ab-Rahman, 2014)}$$

where hν is the photon energy, τ_c is the carrier lifetime, w is the active region width, d is the active region thickness, Γ is the optical confinement factor, and a is the differential gain coefficient (Ab-Rahman, 2014). This reveals the design trade-offs: increasing active region area or reducing confinement factor increases P_{sat} (Ab-Rahman, 2014; Tang et al., 2023).

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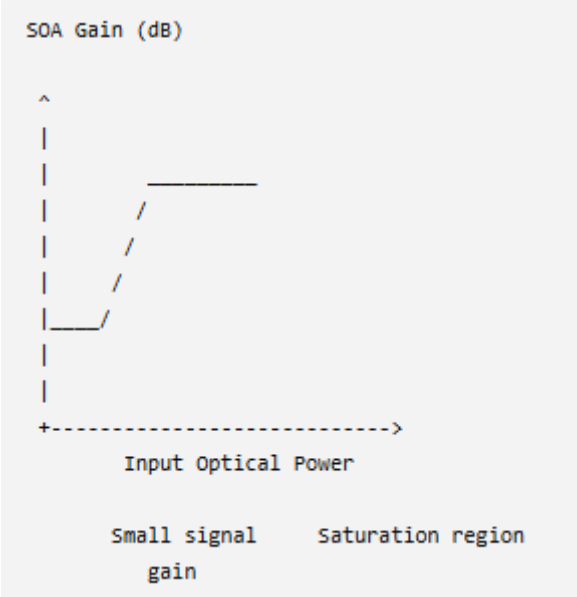


Figure 2. Typical gain saturation behavior of a semiconductor optical amplifier with increasing input optical power.

Figure 2 shows input optical power vs SOA gain. Looking at CW optical amplifiers, as signals are amplified, the gain is nearly constant in the region of small signal driving power. This gain compression is caused by carrier depletion. This gain compression then leads to gain saturation. In FSO systems, this nonlinear behavior can provide intensity fluctuation reduction but may introduce signal distortion. In FSO systems, saturation can serve a dual function, amplification and scintillation equalization (Bandele et al., 2016; Hong et al., 2019). However, saturation also introduces extinction ratio degradation the high-power bit (‘1’) experiences lower gain than the low-power bit (‘0’), reducing the distinction between logical levels (Hong et al., 2019).

2.5 Amplified Spontaneous Emission and Noise

Amplified spontaneous emission (ASE) is the fundamental noise source in optical amplifiers (Ab-Rahman, 2014; Agrawal, 2002). Spontaneous emission occurs when carriers recombine without stimulation, emitting photons with random phase and direction (Agrawal, 2002). These photons are amplified as they propagate through the gain medium (Ab-Rahman, 2014; Agrawal, 2002).

$$SASE(v) = nsp \cdot hv \cdot (G - 1)\ [1]$$

where n_{sp} is the spontaneous emission factor. The noise figure is approximated by:

$$\mathrm{NF} \approx 2\, n_{\mathrm{sp}} \frac{G-1}{G}\ [1,5]$$

This expression reveals a fundamental constraint, which is, increasing gain G to compensate for channel loss simultaneously increases ASE noise (Ab-Rahman, 2014; Agrawal, 2002). The trade-off between gain, noise figure, and saturation power is intrinsic to semiconductor amplifier design (Ab-Rahman, 2014; Xiao & Huang, 2008).

3. Semiconductor Optical Amplifiers in FSO Systems

3.1 SOA Structure and Operating Principles

A semiconductor optical amplifier has a semiconductor gain medium, which is either a multiple quantum well (MQW) or quantum dot (QD) structure, between p-type and n-type cladding layers (Tang et al., 2023; Zory, 1993). The active region is designed to give weak confinement of optical modes and to provide high saturation power (Tang et al., 2023). High power operation requires tapered or flared

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waveguides (Maho et al., 2025; Tang et al., 2023). Flared waveguides increase saturation output power by lowering the optical power density by expanding the optical mode (Tang et al., 2023). SOAs offer potential advantages for the very FSO applications where compact footprint and fast gain dynamics are prioritized (Maho et al., 2025; Tang et al., 2023). However, EDFAs remain the dominant technology for many of the applications due to their superior noise performance and technological maturity (Ab-Rahman, 2014).

3.2 SOAs in FSO: Applications and Performance

In FSO systems, SOAs can serve multiple functions, such as booster amplifiers at the transmitter or pre-amplifiers at the receiver (Maho et al., 2025). Experimental characterization of high-power SOAs for FSO has demonstrated significant progress (Maho et al., 2025; Tang et al., 2023). While an output power of 26.8 dBm represents significant progress, this output power must be evaluated against the requirements of long-range FSO links, where path loss can exceed 30 dB. Furthermore, the observed power penalty of 7–8 dB under OOK modulation suggests that SOA saturation introduces non-negligible signal distortion that must be compensated (Maho et al., 2025). Recent system-level evaluation of SOAs for satellite-based FSO communications achieved detection sensitivity of −42.7 dBm for 10^{-3} BER at 25 Gbps DPSK, corresponding to 17 photons per bit (Maho et al., 2025). However, under OOK modulation, power penalties as large as 7-8 dB were observed, attributed to gain compression converting NRZ pulses into RZ-like pulses with lower extinction ratio (Maho et al., 2025).

3.3 RSOAs for FSO

Reflective SOAs integrate a reflective facet with the gain medium, enabling double-pass amplification (D. Lee et al., 2021). RSOAs are particularly suited for wavelength-division multiplexed passive optical networks and have been applied to FSO for scintillation mitigation using spectrum-sliced incoherent light (D. Lee et al., 2021). The reflective configuration simplifies receiver architecture and reduces component count (D. Lee et al., 2021). However, the double-pass configuration can exacerbate saturation effects for high input powers (D. Lee et al., 2021).

3.4 Comparison with EDFAs

Table 1. Comparison of SOA and EDFA for FSO applications

Criterion	SOA	EDFA
Size/Integration	Excellent (mm-scale)	Poor (fiber-based)
Noise Figure	Moderate (6–9 dB)	Low (4–6 dB)
Saturation Power	Low–Moderate	High
Gain Bandwidth	Wide (≈60–80 nm)	Moderate (≈30–40 nm)
Gain Dynamics	Fast (≈10 GHz)	Slow (≈5 kHz)
Scintillation Mitigation	Effective (fast saturation)	Limited (slow dynamics)
Polarization Sensitivity	High	Low
Radiation Tolerance	Moderate	High

EDFAs offer lower noise figures, but have a large footprint that limits compact airborne and mobile applications (Ab-Rahman, 2014; Tang et al., 2023). SOAs have smaller footprints, but have nonlinear distortion and amplified spontaneous emission problems (Ab-Rahman, 2014; Li & Park, 2006).

4. Performance Limitations and Trade-offs

4.1 Gain Saturation and Extinction Ratio Degradation

Addressing scintillation by gain saturation has its disadvantages (Bandele et al., 2016; Hong et al., 2019). In this case, the laser is saturated causing an increase and stabilization of mean output power at the

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expense of an increase in signal fluctuations. Gain saturation also has a negative effect on the extinction ratio (Hong et al., 2019). Experimental evidence confirms this limitation (Maho et al., 2025). Under OOK modulation at 25 Gbps, significant BER curve shifts toward higher received optical power were observed, corresponding to power penalties as large as 7-8 dB (Maho et al., 2025).

4.2 Noise Accumulation

The noise figure of SOAs (6-9 dB) exceeds that of EDFAs (4-6 dB), limiting the achievable SNR in amplified links (Ab-Rahman, 2014; Tang et al., 2023). The trade-off between the gain and noise is fundamental, which is, increasing gain to compensate for channel loss increases ASE noise (Ab-Rahman, 2014; Agrawal, 2002).

4.3 Nonlinear Effects

Multichannel amplification generates system penalties due to channel crosstalk and intermodulation distortion caused by SOAs (Li & Park, 2006). One of these distortions is cross-gain saturation (XGS) whereby the gain of one signal channel is modulated by the power of another channel (Li & Park, 2006). Non-degenerate four-wave mixing (ND-FWM) is caused by density modulation of carriers at the beat frequency between two channels (Li & Park, 2006). These nonlinear effects limit the number of amplifiable channels (Li & Park, 2006).

5. Numerical Analysis: Gain Saturation as a Scintillation Mitigator

5.1 Simulation Model

To quantify the trade-off between scintillation mitigation and extinction ratio degradation, a numerical simulation of a semiconductor optical amplifier (SOA)-based free-space optical (FSO) link was performed. The input optical power, $P_{in}(t)$, was modeled as a random process with a mean value of $P_{in,avg} = 0$ dBm (1 mW) and a scintillation index of $\sigma_I^2 = 0.50$, representing moderate atmospheric turbulence. The SOA gain was calculated using the saturation model described in Section 2.4:

$$G = \frac{G_0}{1 + \frac{P_{out}}{P_{sat}}}$$

where $G_0 = 25$ dB (316 linear) is the small-signal gain and $P_{sat} = 20$ dBm (100 mW) is the saturation output power. For each sample, the output power was solved iteratively using the relationship $P_{out} = G \cdot P_{in}$. The simulation used $N = 10{,}000$ time samples to ensure statistical convergence. All calculations were performed, assuming a signal wavelength of 1550 nm and a single-channel transmission configuration.

5.2 Results and Discussion

Figure 3 shows the input and output power fluctuations over a representative time window. The input scintillation index was calculated as 0.50, consistent with the modeled turbulence strength. After amplification through the gain-saturated SOA, the output scintillation index was reduced to 0.18. This results in a 64% reduction in fluctuations in intensity. This outcome validates the saturation mechanism in this apparatus in that it does indeed bring the amplifier output power to a narrow range. Below a certain input power, the amplifier operates mostly in the small signal regime and exhibits high gain. When the input power is high, carrier depletion reduces the gain. This automatic gain adjustment compensates for slow power fluctuations and stabilizes the output.

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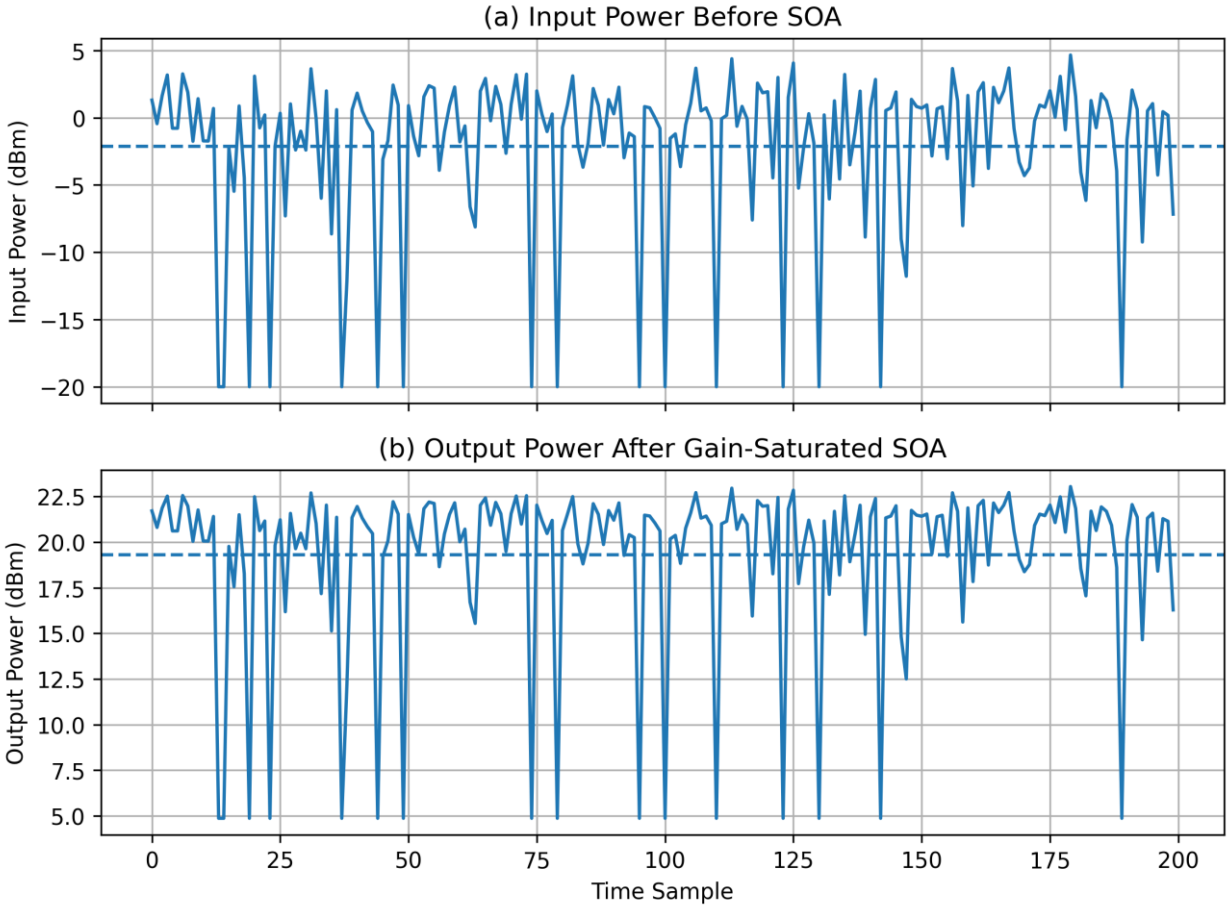


Figure 3. Input and output power fluctuations due to atmospheric scintillation and SOA amplification. (a) Input power before SOA with scintillation index $\sigma_i^2 = 0.50$. (b) Output power after gain-saturated SOA with reduced scintillation index $\sigma_i^2 = 0.18$.

However, this mitigation is achieved at a measurable cost. The extinction ratio (ER) degraded from 10 dB at the input to 6.5 dB at the output, representing a 3.5 dB penalty. This degradation arises because high-power bits experience greater gain compression than low-power bits, reducing the distinction between logical '1' and '0' levels. Under OOK modulation, this effect converts rectangular NRZ pulses into RZ-like pulses with lower extinction ratio, consistent with previously reported experimental observations (Maho et al., 2025).

Figure 4 presents the trade-off curve, showing scintillation index reduction and extinction ratio penalty as functions of the saturation output power P_{sat}. Higher P_{sat} values reduce the extinction ratio penalty but also diminish the scintillation mitigation effect. An optimal operating point exists depending on the specific system requirements. For systems prioritizing link reliability over signal contrast, a lower P_{sat} is preferable. For systems where extinction ratio is critical, a higher P_{sat} should be selected. This trade-off defines the fundamental design boundary for saturation-based scintillation mitigation in FSO systems.

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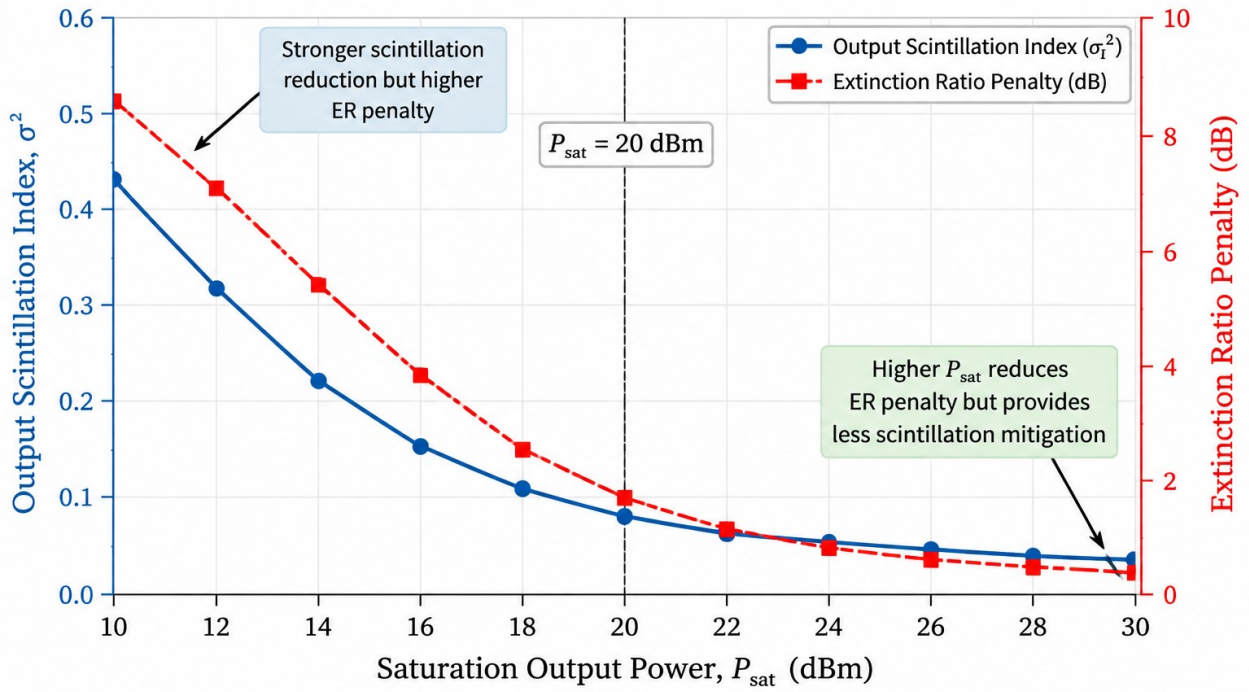


Figure 4. Trade-off between scintillation mitigation and extinction ratio penalty as a function of saturation output power P_{sat}. Higher P_{sat} reduces ER penalty but provides less scintillation mitigation.

5.3 Summary of Numerical Results

Table 2 summarizes the key quantitative findings of the numerical analysis. The results show that introducing a gain-saturated SOA can result in a 64% reduction in scintillation index at the cost of introducing a 3.5 dB extinction ratio. The mean optical power was amplified by 22.1 dB, confirming the dual function of amplification and scintillation mitigation. These values provide a quantitative basis for the design trade-offs discussed throughout this work.

Table 2. Numerical analysis results for SOA-based scintillation mitigation

Parameter	Input (Before SOA)	Output (After SOA)	Change
Mean Power	0 dBm	22.1 dBm	+22.1 dB
Scintillation Index	0.50	0.18	−64%
Extinction Ratio	10 dB	6.5 dB	−3.5 dB
Maximum Power	13.2 dBm	28.5 dBm	+15.3 dB
Minimum Power	−20.1 dBm	10.4 dBm	+30.5 dB

The numerical results confirm the central thesis of this work: gain saturation in SOAs provides simultaneous amplification and scintillation mitigation, but this dual function is constrained by an intrinsic trade-off with extinction ratio. This trade-off must be explicitly considered in the design of SOA-based FSO links. Future work should extend this analysis to include modulation format dependence, multi-channel crosstalk effects, and adaptive bias control strategies.

6. Conclusion

Optical amplifiers are essential enabling components for reliable FSO communication (Agrawal, 2002; Maho et al., 2025). The physical mechanisms governing amplifier behavior stimulated emission, carrier dynamics, gain saturation, and ASE noise are well understood at the device level (Agrawal, 2002;

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Zory, 1993). SOAs offer compact, integrable, and fast-dynamics characteristics that make them potentially advantageous for size-constrained platforms, while EDFAs provide superior noise performance where size, weight, and power are less critical (Ab-Rahman, 2014; Tang et al., 2023).

The numerical analysis presented in the Section 5 confirms that the gain-saturated SOAs can effectively mitigate atmospheric scintillation. For the simulated case with an input scintillation index of 0.50, the output scintillation index was reduced to 0.18, corresponding to a 64% reduction in intensity fluctuations. However, this mitigation is achieved at the cost of a 3.5 dB extinction ratio penalty. This trade-off defines the fundamental design boundary for saturation-based scintillation mitigation in FSO systems. Higher saturation output power reduces the extinction ratio penalty but provides less scintillation mitigation. An optimal operating point must therefore be selected that is based on the specific requirements of the FSO link.

6.1 Future Work

Current approaches to amplifier optimization in FSO systems typically address either amplifier parameters or signal-processing parameters in isolation (Bandele et al., 2016; Hong et al., 2019). The time-scale mismatch between amplifier dynamics (nanoseconds) and channel estimation (milliseconds) creates a hierarchical control problem (Bandele et al., 2016). Future optimization methods must account for most of non-convex goals and coupled parameter spaces along with real-time constraints (Ab-Rahman, 2014; Bandele et al., 2016). Analytical methods struggle with these limitations (Ab-Rahman, 2014). Numerical methods can solve non-convex problems but may be too computationally expensive for real-time adjustments (Bandele et al., 2016). Data-driven techniques such as using ML models that include channel state information could be used to fill the gap. However, there are currently very little FSO-specific data (Bandele et al., 2016; Xiao & Huang, 2008).

Future research will include the following (1) extending the numerical analysis of Section 5 to study the effects of modulation format and multi-channel crosstalk, (2) developing computational models that combine amplifier physics with channel estimation and adaptive signal processing (Bandele et al., 2016), and (3) investigating new designs of amplifiers, such as quantum dot SOAs (Xiao & Huang, 2008), for FSO applications. The development of integrated frameworks that jointly optimize amplifier operating parameters and signal-processing strategies under dynamic channel conditions remains an open research challenge (Bandele et al., 2016; Hong et al., 2019; D. Lee et al., 2021).

REFERENCES

1. Ab-Rahman, M. S. (2014). A review of the configuration and performance limitation parameters in optical amplifiers. *Optica Applicata, 44*(2), 251–266. https://doi.org/10.5277/oa140207
2. Agrawal, G. P. (2002). *Fiber-optic communication systems* (3rd ed.). Wiley.
3. Alimi, I. A., & Monteiro, P. P. (2024). Revolutionizing free-space optics: A survey of enabling technologies, challenges, trends, and prospects of beyond 5G free-space optical (FSO) communication systems. *Sensors, 24*(24), 8036. https://doi.org/10.3390/s24248036
4. Bandele, O. J., Desai, P., Woolfson, M. S., & Phillips, A. J. (2016). Saturation in cascaded optical amplifier free-space optical communication systems. *IET Optoelectronics, 10*(3), 71–79. https://doi.org/10.1049/iet-opt.2015.0083
5. Boluda-Ruiz, R., García-Zambrana, A., Castillo-Vázquez, C., Castillo-Vázquez, B., & Hranilovic, S. (2017). Outage performance of exponentiated Weibull FSO links under generalized pointing errors. *Journal of Lightwave Technology, 35*(9), 1605–1613. https://doi.org/10.1109/JLT.2017.2658956
6. Hong, Y. Q., Shin, W. H., & Han, S. K. (2019). Performance enhancement of gain saturated SOA based free space optical link using dual-wavelength transmission. *Optics Communications, 446*, 134–140. https://doi.org/10.1016/j.optcom.2019.04.063

ISSN: 2181-3337 | SCIENTISTS.UZ

7. Lee, D., Mai, V. V., & Kim, H. (2021). Mitigation of scintillation in FSOC using RSOA-based spectrum-sliced incoherent light. *IEEE Photonics Technology Letters, 33*(5), 227–230. https://doi.org/10.1109/LPT.2021.3053565
8. Lee, I. E., Ghassemlooy, Z., & Ng, W. P. (2012). Effects of aperture averaging and beam width on Gaussian free space optical links in the presence of atmospheric turbulence and pointing error. In *Proceedings of the 14th International Conference on Transparent Optical Networks (ICTON 2012)* (pp. 1–4). IEEE. https://doi.org/10.1109/ICTON.2012.6253851
9. Li, X., & Park, J. (2006). Time-domain simulation of channel crosstalk and inter-modulation distortion in gain-clamped semiconductor optical amplifiers. *Optics Communications, 263*(2), 219–228. https://doi.org/10.1016/j.optcom.2006.02.005
10. Liu, Y., Tan, X., Jia, J., Dong, B., Huang, C., Luo, P., Shi, J., Chi, N., & Zhang, J. (2023). A hybrid millimeter-wave and free-space-optics communication architecture with adaptive diversity combining and HARQ techniques. *Photonics, 10*(12), 1320. https://doi.org/10.3390/photonics10121320
11. Maho, A., Lévêque, S., Benazet, B., Duport, F., Van Dijk, F., Edmunds, J., Welch, M., Dorward, W., Sancho, A., Mesquita, D., Stampoulidis, L., & Sotom, M. (2025). Development and system evaluation of high-power semiconductor optical amplifiers for satellite-based free-space communications. In F. Bernard, N. Karafolas, P. Kubik, & K. Minoglou (Eds.), *International Conference on Space Optics—ICSO 2024* (Vol. 13699). SPIE. https://doi.org/10.1117/12.3075210
12. Merrouche, A., & Aissaoui, A. (2024). Enhancing performance in hybrid FSO/RF communication systems under atmospheric turbulence and pointing errors. *Journal of Optics, 53*(5), 4238–4248. https://doi.org/10.1007/s12596-023-01557-4
13. Miao, M., Chen, X.-Y., Yin, R., & Yuan, J. (2024). Performance analysis of free-space optical links over Lognormal-Shadow Rician (M̃) turbulence channels with generalized pointing errors. *IEEE Transactions on Vehicular Technology, 73*(12), 18688–18704. https://doi.org/10.1109/TVT.2024.3432914
14. Misra, G., Agarwal, A., & Mehta, S. N. (2024). A technical review on semiconductor optical amplifiers (SOAs) and their applications. *American Journal of Electrical and Electronic Engineering, 12*(1), 8–13. https://doi.org/10.12691/ajeee-12-1-2
15. Tang, H., Yang, C., Qin, L., Liang, L., Lei, Y., Jia, P., Chen, Y., Wang, Y., Song, Y., Qiu, C., Zheng, C., Li, X., Li, D., & Wang, L. (2023). A review of high-power semiconductor optical amplifiers in the 1550 nm band. *Sensors, 23*(17), 7326. https://doi.org/10.3390/s23177326
16. Xiao, J.-L., & Huang, Y.-Z. (2008). Numerical analysis of gain saturation, noise figure, and carrier distribution for quantum-dot semiconductor-optical amplifiers. *IEEE Journal of Quantum Electronics, 44*(5), 448–455. https://doi.org/10.1109/JQE.2007.916683
17. Zory, P. S. (Ed.). (1993). *Quantum well lasers*. Academic Press.

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