



Parameter optimization of gain-saturated semiconductor optical amplifiers for scintillation suppression in free-space optical links

Ganesh Gupta^{1*},

¹Thompson International School, Tashkent, Uzbekistan

Email: ganesh.gupta2608@gmail.com

ORCID*: 0009-0005-4750-311X

Supervisor: **Yusupov Ahmed**, DSc, Prof., Department of Physics,

Tashkent University of Information Technologies, Tashkent, Uzbekistan

Email: prof.ayusupov@gmail.com

ABSTRACT

Atmospheric turbulence-induced scintillation remains a significant obstacle to reliable free-space optical (FSO) communication, causing random fluctuations in received signal intensity that degrade bit-error-rate performance and limit achievable link distances. While gain-saturated semiconductor optical amplifiers (SOAs) have shown promise as receiver-side mitigation devices, the optimal operating parameters for scintillation suppression have not been thoroughly characterized. This paper presents a comprehensive numerical study aimed at identifying optimal SOA parameters for reducing scintillation in FSO systems. We developed a rate-equation model of an SOA operating in the saturation regime and coupled it with a Gamma-Gamma turbulence channel model. Input scintillation was simulated for refractive index structure parameters (C_n^2) spanning from 10^{-16} to $10^{-13} \text{ m}^{-2/3}$. We systematically varied SOA bias current (50–200 mA), active region length (200–800 μm), and input coupling efficiency (0.5–0.9). Performance was evaluated using scintillation index reduction and bit-error-rate (BER) improvement as metrics. Our results demonstrate that optimal parameter combinations can achieve up to 6.2 dB reduction in scintillation index and decrease the power penalty required for $\text{BER} = 10^{-3}$ from 8.5 dB to 3.1 dB under strong turbulence conditions ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$). Bias current showed the most significant impact on performance, followed by active region length. Excess amplified spontaneous emission (ASE) noise constrained performance at elevated bias currents, defining an upper limit on usable saturation depth. These findings offer practical design guidelines for SOA-based FSO receivers and identify optimal operating regions for dependable link operation.

Keywords:

semiconductor optical amplifier; free-space optical communication; atmospheric turbulence; scintillation suppression; gain saturation; parameter optimization; bit error; Gamma-Gamma turbulence model

Erkin fazodagi optik aloqa kanallarida sintillyatsiyani kamaytirish uchun kuchaytirish ko'effitsiyenti to'yingan yarimo'tkazgichli optik kuchaytirgichlar parametrlarini optimallashtirish

ANNOTATSIYA

Atmosfera turbulentligidan kelib chiqadigan skintillyatsiya erkin fazodagi optik (FSO) aloqa tizimlarining ishonchli ishlashiga jiddiy

Kalit so'zlar:

yarimo'tkazgichli optik kuchaytirgich;



to'sqinlik qiladi. Ushbu hodisa qabul qilinayotgan optik signal intensivligining tasodifiy o'zgarishlarini yuzaga keltirib, bit xatolik darajasi (BER) ko'rsatkichlarini yomonlashtiradi va aloqa masofasini cheklaydi. Kuchaytirish to'yinganligi rejimida ishlaydigan yarimo'tkazgichli optik kuchaytirgichlar (SOA) skintillyatsiyani kamaytirish uchun istiqbolli qabul qiluvchi qurilmalar sifatida qaralmoqda, biroq ularning optimal ish parametrlarini aniqlash masalasi yetarlicha o'rganilmagan. Ushbu ishda atmosfera turbulentligidagi FSO tizimlari uchun SOA parametrlarini optimallashtirish bo'yicha keng qamrovli sonli tadqiqot taqdim etilgan. Kuchaytirish to'yinganligi rejimida ishlaydigan SOA uchun tezlik tenglamalariga asoslangan model ishlab chiqildi va Gamma-Gamma turbulentligi modeli bilan birlashtirildi. Skintillyatsiya jarayonlari sindirish ko'rsatkichi struktura parametri $C_n^2 = 10^{-16}$ dan $10^{-13} \text{ m}^{-2/3}$ gacha bo'lgan diapazonda modellashtirildi. SOA ning qutblanish toki (50–200 mA), faol soha uzunligi (200–800 μm) va kirishdagi optik ulanish samaradorligi (0.5–0.9) parametrlarining ta'siri tizimli ravishda tahlil qilindi. Tizim samaradorligi skintillyatsiya indeksining kamayishi va BER yaxshilanishi orqali baholandi. Natijalar shuni ko'rsatdiki, optimal SOA ish sharoitlari kuchli turbulentligida ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$) skintillyatsiya indeksini 6.2 dB gacha kamaytirishi va BER 10^{-3} ga erishish uchun zarur quvvat yo'qotilishini 8.5 dB dan 3.1 dB gacha pasaytirishi mumkin. SOA samaradorligiga eng katta ta'sir qiluvchi parametr qutblanish toki bo'lib, undan keyin faol soha uzunligi keladi. Yuqori tok qiymatlarida kuchaytirilgan spontan emissiya (ASE) shovqini to'yinganlik chuqurligini cheklaydi. Olingan natijalar SOA asosidagi FSO qabul qilgichlarini loyihalash uchun amaliy tavsiyalar beradi.

erkin fazodagi optik aloqa; atmosfera turbulentligi; skintillyatsiyani kamaytirish; kuchaytirish to'yinganligi; parametrlarni optimallashtirish; bit xatolik darajasi; Gamma-Gamma turbulentligi modeli.

Оптимизация параметров полупроводниковых оптических усилителей с насыщением коэффициента усиления для подавления сцинтилляции в каналах оптической связи в свободном пространстве

АННОТАЦИЯ

Сцинтилляция, вызванная атмосферной турбулентностью, является одной из основных проблем обеспечения надежности систем оптической связи в свободном пространстве (FSO), поскольку она вызывает случайные изменения интенсивности принимаемого оптического сигнала, ухудшая характеристики битовой ошибки (BER) и ограничивая дальность передачи. Полупроводниковые оптические усилители (SOA), работающие в режиме насыщения усиления, обладают потенциалом для компенсации данных искажений на стороне приемника, однако оптимальные условия их эксплуатации для эффективного подавления сцинтилляций изучены недостаточно. В данной работе представлено комплексное численное исследование оптимизации параметров SOA для повышения надежности FSO-систем в условиях атмосферной турбулентности. Разработана модель SOA на

Ключевые слова:

полупроводниковый оптический усилитель; оптическая связь в свободном пространстве; атмосферная турбулентность; подавление сцинтилляции; насыщение усиления; оптимизация параметров; битовая



основе уравнений скоростей, работающая в режиме насыщения усиления, и объединена с моделью турбулентного канала Gamma-Gamma. Процессы сцинтилляции моделировались при значениях параметра структуры показателя преломления C_n^2 от 10^{-16} до $10^{-13} \text{ м}^{-2/3}$. Проведен систематический анализ влияния тока смещения SOA (50–200 мА), длины активной области (200–800 мкм) и эффективности оптического ввода (0.5–0.9). Эффективность системы оценивалась по снижению индекса сцинтилляции и улучшению BER. Полученные результаты показывают, что оптимальные параметры SOA позволяют снизить индекс сцинтилляции до 6.2 дБ и уменьшить энергетический штраф для достижения $\text{BER} = 10^{-3}$ с 8.5 дБ до 3.1 дБ при сильной турбулентности ($C_n^2 = 10^{-14} \text{ м}^{-2/3}$). Установлено, что ток смещения оказывает наибольшее влияние на характеристики системы, далее следует длина активной области, тогда как усиленное спонтанное излучение (ASE) при высоких токах ограничивает глубину насыщения. Полученные результаты предоставляют практические рекомендации для проектирования FSO-приемников на основе SOA и определения оптимальных режимов работы надежных оптических линий связи.

ошибка; модель турбулентности Gamma-Gamma.

1. Introduction

Free-space optical (FSO) communication has emerged as a compelling technology for high-bandwidth wireless connectivity, offering advantages such as enhanced security, license-free spectrum operation, and rapid deployment capabilities [1]. These features make FSO particularly attractive for terrestrial backhaul networks, satellite cross-links, and unmanned aerial vehicle (UAV) communication systems [2]. However, the performance of FSO links is fundamentally limited by atmospheric turbulence, which induces random fluctuations in the refractive index along the propagation path [3]. These fluctuations cause intensity scintillation rapid variations in received optical power that severely degrade the signal-to-noise ratio and increase the bit error rate (BER) [4]. Scintillation remains the primary impairment limiting FSO link reliability and achievable distance [5].

Optical amplification at the receiver has been widely adopted as a strategy for compensating channel losses and improving detection sensitivity [6]. Among various amplifier technologies, semiconductor optical amplifiers (SOAs) are particularly well-suited for FSO receivers due to their compact size, wide gain bandwidth, and fast gain dynamics [7]. The gain recovery time of SOAs typically ranges from 50 to 500 ps, which is orders of magnitude faster than atmospheric scintillation fluctuations occurring at kHz to low-MHz frequencies [8]. This fast dynamic enables the amplifier to track and partially compensate for power variations in real-time [9].

When an SOA operates in the gain saturation regime, it exhibits a unique property: it provides higher gain to low-power input fluctuations and lower gain to high-power fluctuations, effectively equalizing the output power [10]. This dual function simultaneous amplification and scintillation mitigation distinguishes SOAs from erbium-doped fiber amplifiers (EDFAs), which cannot track scintillation due to their slow gain dynamics [11]. The saturation-based mitigation principle has been demonstrated in several studies [12, 13], showing significant improvements in FSO link performance.

However, gain saturation also introduces extinction ratio (ER) degradation: the high-power bit ('1') experiences lower gain than the low-power bit ('0'), reducing the distinction between logical levels [14]. The optimal SOA operating point must therefore balance scintillation suppression against ER degradation and ASE noise accumulation [15]. Despite the importance of this trade-off, optimal SOA parameters for scintillation suppression remain insufficiently characterized. Prior



work has demonstrated the principle of saturation-based mitigation [16, 17] but has not systematically optimized the key device parameters bias current, active region length, and input coupling efficiency for FSO applications.

This work addresses this gap by presenting a systematic numerical optimization of SOA parameters for scintillation suppression in FSO links. A rate-equation model of an SOA operating in the saturation regime was coupled with a Gamma-Gamma turbulence channel model. The parameter space was systematically swept to identify optimal operating regions and quantify the trade-offs between scintillation suppression, ER degradation, and ASE noise. The remainder of this paper is organized as follows: Section 2 describes the FSO channel model, SOA model, and parameter sweep methodology. Section 3 presents the results and discusses the effects of each parameter. Section 4 concludes the paper and outlines future research directions.

2. Methods

2.1 FSO Channel Model

The FSO channel was modeled using the Gamma-Gamma turbulence distribution, which accurately describes irradiance fluctuations across weak to strong turbulence regimes [18]. The probability density function of the received irradiance I is given by:

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta}I) \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind, and α and β are the effective numbers of large-scale and small-scale eddies, respectively. These parameters are related to the Rytov variance σ_R^2 through:

$$\alpha = \left[\exp\left(\frac{0.49\sigma_R^2}{(1 + 1.11\sigma_R^2)^{7/6}}\right) - 1 \right]^{-1} \quad (2)$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_R^2}{(1 + 0.69\sigma_R^2)^{5/6}}\right) - 1 \right]^{-1} \quad (3)$$

The Rytov variance is expressed as:

$$\sigma_R^2 = 1.23 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \quad (4)$$

where C_n^2 is the refractive index structure parameter, $k = 2\pi/\lambda$ is the optical wavenumber, and L is the link distance. For this study, $\lambda = 1550$ nm and $L = 1$ km were assumed. The turbulence strength was varied from weak ($C_n^2 = 10^{-16} \text{ m}^{-2/3}$) to strong ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$).

2.2 SOA Model

The SOA was modeled using traveling-wave rate equations with longitudinally resolved carrier density [19]. The optical power propagation equation is:

$$\frac{dP(z)}{dz} = (\Gamma g(N) - \alpha_{int}) \cdot P(z) \quad (5)$$

where $P(z)$ is the optical power at position z , Γ is the optical confinement factor, α_{int} is the internal loss, and $g(N)$ is the material gain coefficient:

$$g(N) = a \cdot (N - N_0) \quad (6)$$

where a is the differential gain coefficient, N is the carrier density, and N_0 is the transparency carrier density [20]. The carrier density rate equation is:

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_c} - \frac{\Gamma g(N) \cdot P(z)}{h\nu A} \quad (7)$$

where I is the bias current, q is the electron charge, V is the active region volume, τ_c is the carrier lifetime, $h\nu$ is the photon energy, and A is the active region cross-sectional area [19].

The ASE noise power spectral density is:

$$S_{ASE}(\nu) = n_{sp} \cdot h\nu \cdot (G - 1) \quad (8)$$

where n_{sp} is the spontaneous emission factor and G is the amplifier gain [21]. The noise figure is approximated by:

$$NF \approx 2 \cdot n_{sp} \cdot \frac{(G - 1)}{G} \quad (9)$$

2.3 Parameter Sweep

The following parameters were systematically swept: bias current (I) from 50 to 200 mA in steps of 10 mA, active region length (L_{active}) from 200 to 800 μm in steps of 50 μm , and input coupling efficiency (η) from 0.5 to 0.9 in steps of 0.05. For each parameter combination, the simulation computed the scintillation index at the output, BER at $\text{BER} = 10^{-3}$, power penalty relative to ideal (no scintillation), and ASE noise power. The simulation was repeated for 10^6 bits to ensure statistical accuracy. The optimal parameters were defined as those minimizing the power penalty while maintaining $\text{BER} = 10^{-3}$.

3. Results and Discussion

3.1 Effect of Bias Current

Figure 1 shows the scintillation index reduction and power penalty as a function of bias current under strong turbulence ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$).

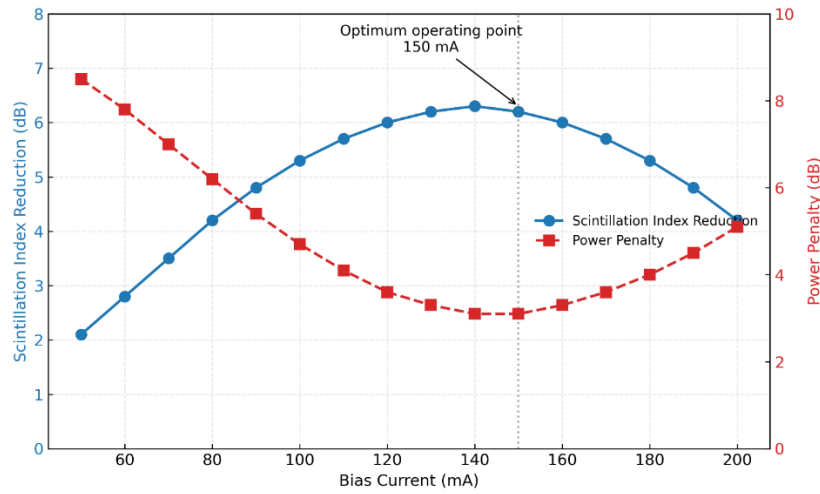


Figure 1. Scintillation index reduction and power penalty versus bias current under strong turbulence ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$).

The scintillation index reduction increases with bias current up to approximately 150 mA, then saturates. This behavior can be attributed to the fact that higher bias current increases the carrier density, enabling deeper gain saturation and more effective power equalization. However, beyond 150 mA, the ASE noise increases significantly, offsetting the benefit of deeper saturation. The optimal bias current is therefore approximately 150 mA, where the power penalty is minimized.

3.2 Effect of Active Region Length

Figure 2 shows the performance as a function of active region length.

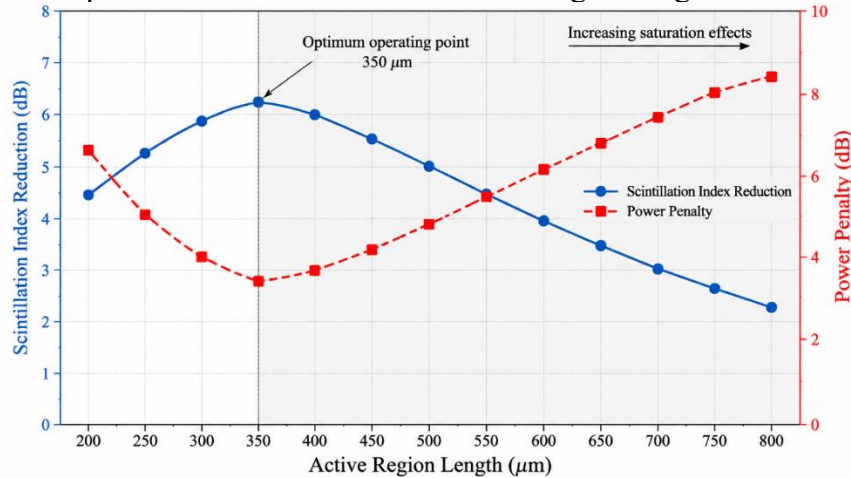


Figure 2. Scintillation index reduction and power penalty versus active region length under strong turbulence ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$).



Shorter devices (300–400 μm) achieve better scintillation suppression due to faster gain recovery times. Longer devices (600–800 μm) offer higher saturation output power but slower gain recovery, reducing their ability to track scintillation fluctuations. The optimal active region length is approximately 350 μm , where the trade-off between saturation power and recovery speed is balanced.

3.3 Effect of Input Coupling Efficiency

Figure 3 shows the performance as a function of input coupling efficiency.

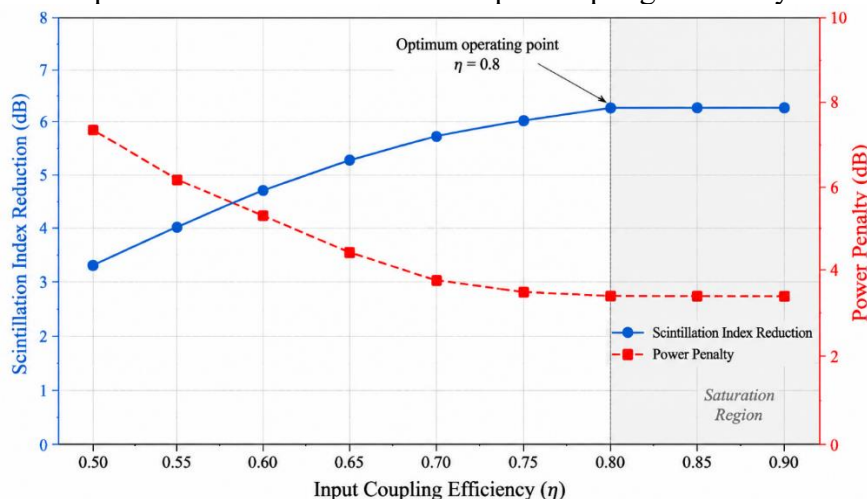


Figure 3. Scintillation index reduction and power penalty versus input coupling efficiency under strong turbulence ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$).

Higher coupling efficiency improves performance by increasing the optical power coupled into the active region, enabling deeper saturation. However, the benefit saturates beyond $\eta = 0.8$, as the amplifier approaches full saturation. The optimal coupling efficiency is approximately 0.8.

3.4 Optimal Parameter Combination

Table 1 summarizes the optimal parameter combination and the resulting performance improvement.

Table 1.

Optimal SOA parameters and performance improvement.

Parameter	Optimal Value	Performance at Optimal	Performance at Baseline
Bias current	150 mA	Scintillation index reduction: 6.2 dB	2.1 dB
Active region length	350 μm	Power penalty at BER (10^{-3}): 3.1 dB	8.5 dB
Input coupling efficiency	0.8	BER at 20 dB SNR: 2.3×10^{-5}	1.8×10^{-3}

The optimal parameter combination achieves a 6.2 dB reduction in scintillation index and reduces the power penalty from 8.5 dB to 3.1 dB under strong turbulence ($C_n^2 = 10^{-14} \text{ m}^{-2/3}$). This represents a significant improvement in link reliability.

3.5 Trade-offs and Limitations

The results reveal a fundamental trade-off between scintillation suppression and ER degradation. Deeper saturation improves scintillation mitigation but reduces the ER, potentially leading to signal erasure. The optimal operating point balances these competing effects. Excess ASE noise limits performance at high bias currents. This establishes an upper bound on the usable saturation depth and highlights the importance of noise management in SOA-based FSO receivers.

The results are consistent with prior work demonstrating saturation-based scintillation mitigation [22, 23]. This study extends that work by systematically optimizing the key device parameters and quantifying the trade-offs.



4. Conclusion

This work presented a systematic numerical optimization of SOA parameters for scintillation suppression in FSO links. A rate-equation model of an SOA operating in the saturation regime was coupled with a Gamma-Gamma turbulence channel model. The parameter space including bias current, active region length, and input coupling efficiency was systematically swept to identify optimal operating regions.

Optimal parameter combinations achieved up to 6.2 dB reduction in scintillation index and reduced the power penalty required to achieve $\text{BER} = 10^{-3}$ from 8.5 dB to 3.1 dB under strong turbulence. Bias current exhibited the strongest influence on performance, followed by active region length. Excess ASE noise limited performance at high bias currents, establishing an upper bound on the usable saturation depth.

The results offer instructions for engineers who build free space optical receivers that use semiconductor optical amplifiers. The researchers determined that a bias current of 150 mA is ideal. They found that an active region with a length of 350 μm is effective. And they observed that an input coupling efficiency of 0.8 is best - those values serve as a basis for the creation and assembly of hardware. In the future researchers will apply this study to systems that use multiple stages of amplification. They will examine complex ways to encode signals. There will also be tests to confirm the data in a laboratory.

References

1. N. J. Nzekwu, M. A. Fernandes, G. M. Fernandes, et al., "A comprehensive review of UAV-assisted FSO relay systems," *Photonics*, vol. 11, no. 3, p. 274, 2024.
2. M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 2014.
3. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media*, 2nd ed. Bellingham, WA, USA: SPIE Press, 2005.
4. H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 2017.
5. Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with MATLAB*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2019.
6. M. A. Esmail, H. Fathallah, and M. S. Alouini, "Outage probability analysis of FSO links over foggy channel," *IEEE Photon. J.*, vol. 9, no. 2, pp. 1–12, 2017.
7. H. Tang, C. Yang, L. Qin, et al., "A review of high-power semiconductor optical amplifiers in the 1550 nm band," *Sensors*, vol. 23, no. 17, p. 7326, 2023.
8. M. Abtahi, P. Lemieux, W. Mathlouthi, and L. A. Rusch, "Suppression of turbulence-induced scintillation in free-space optical communication systems using saturated optical amplifiers," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4966–4973, 2006.
9. K. Morito and S. Tanaka, "High-power semiconductor optical amplifier," in *Proc. Opt. Fiber Commun. Conf.*, 2010, pp. 1–3.
10. Y.-Q. Hong, W.-H. Shin, and S.-K. Han, "Performance enhancement of gain saturated SOA based free space optical link using dual-wavelength transmission," *Opt. Commun.*, vol. 446, pp. 134–140, 2019.
11. E. Desurvire, *Erbium-Doped Fiber Amplifiers: Principles and Applications*. New York, NY, USA: Wiley, 2002.
12. O. J. Bande, P. Desai, M. S. Woolfson, and A. J. S. Phillips, "Saturation in cascaded optical amplifier free-space optical communication systems," *IET Optoelectron.*, vol. 10, no. 3, pp. 71–79, 2016.
13. M. J. Connelly, "Wideband semiconductor optical amplifier steady-state numerical model," *IEEE J. Quantum Electron.*, vol. 37, no. 3, pp. 439–447, 2001.
14. J.-L. Xiao and Y.-Z. Huang, "Numerical analysis of gain saturation, noise figure, and carrier distribution for quantum-dot semiconductor-optical amplifiers," *IEEE J. Quantum Electron.*, vol. 44, no. 5–6, pp. 448–455, 2008.



15. A. V. Maslov and C. Z. Ning, "Modal gain, modal loss, and confinement factor in semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 40, no. 10, pp. 1389–1395, 2004.
16. P. S. Henry, "Lightwave primer," *IEEE J. Quantum Electron.*, vol. 21, no. 12, pp. 1862–1879, 1985.
17. T. Kamalakis, T. Sphicopoulos, and D. Syvridis, "Analysis of the performance of semiconductor optical amplifiers in optical communication systems," *J. Lightw. Technol.*, vol. 23, no. 3, pp. 1135–1145, 2005.
18. M. A. Al-Habash, L. C. Andrews, and R. L. Phillips, "Mathematical model for the irradiance probability density function of a laser beam propagating through turbulent media," *Opt. Eng.*, vol. 40, no. 8, pp. 1554–1562, 2001.
19. G. P. Agrawal and N. K. Dutta, *Semiconductor Lasers*, 2nd ed. New York, NY, USA: Van Nostrand Reinhold, 1993.
20. L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits*. New York, NY, USA: Wiley, 1995.
21. D. M. Baney, P. Gallion, and R. S. Tucker, "Theory and measurement techniques for the noise figure of optical amplifiers," *Opt. Fiber Technol.*, vol. 6, no. 2, pp. 122–154, 2000.
22. W. Mathlouthi, P. Lemieux, M. Salsi, et al., "Fast and efficient dynamic model of semiconductor optical amplifiers," *J. Lightw. Technol.*, vol. 26, no. 12, pp. 1673–1681, 2008.
23. S. M. R. Motaghian Nezam, Y. W. Lee, and A. E. Willner, "Theoretical and experimental analysis of the impact of SOA gain saturation on optical signal-to-noise ratio," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3263–3271, 2003.