Potential of the Semiconductor Optical Amplifier (SOA) for Future Applications

D. I. Forsyth[1]* and A.J Abdullah Al-Gburi[1]

[1]Department of Electronics and Computer Engineering Technology (JTKEK), Universiti Teknikal Malaysia Melaka (UTeM), Jalan Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

***Corresponding Author**

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ABSTRACT

The semiconductor optical amplifier (soa) has emerged as a transformative technology, poised to influence the future of optical amplification significantly. While traditionally competing with other types of amplifiers, such as the bulky and single-functioning erbium-doped fibre amplifier (edfa), the soa's compact size, multifunctional capabilities and advancing performance metrics position it as a strong candidate for the default choice in next-generation optical systems. Continuous innovations in efficiency, miniaturization, integration, cost-effectiveness and manufacturing techniques concerning this device are rapidly overcoming historical limitations, ensuring its ascendancy in both academic research and industrial applications. This paper explores the evolution of the soa, highlighting key advancements in its development and future prospects. Collectively, all the evidence points to its inevitable dominance in future practical optical communications, mainly by virtue of its adaptivity, either as a standalone competitive device or with hybrid-like integration with other types of amplifiers.

Keywords— semiconductor optical amplifier, SOA, optical amplification, laser technology, future dominance

INTRODUCTION

The main optical amplifier types currently in use today commercially are the erbium-doped fibre amplifier (EDFA), the semiconductor optical amplifier (SOA), the Raman amplifier (RA), the thulium-doped fibre amplifier (TDFA), the praseodymium-doped fibre amplifier (PDFA) and the optical parametric amplifier (OPA) [1]. Each of these types of optical amplifier operates in its own specialized domain, with minimal overlap due to fundamental differences in performance, cost and technical suitability [2]. Currently, about 80% of all amplifiers deployed are EDFAs [3]. The EDFA has been a cornerstone of optical communication systems since the 1990s, providing high-gain, low-noise amplification for C-band (1530–1565 nm) and L-band wavelengths (1565–1625 nm) [4]. However, as network demands evolve, researchers are exploring alternatives that could complement or even replace EDFAs in certain scenarios [5]. These C- and L-bandwidth limitations are incompatible with future networks requiring broader or different spectral ranges (e.g., the O-band for shorter-reach optics) [6]. Future amplifiers will also need to offer more compatibility and better power efficiency, crucial for data centres and space-constrained applications [7]. Apart from the SOA, all the other amplifiers are fibre-based and bulky compared to on-chip amplifiers like the SOA, and emerging technologies such as coherent optics and free-space optical communications may need different amplification approaches [8]. The key demands for the amplifier of the future will be driven by future bandwidth requirements, integration needs and power-efficiency targets utilizing ultra-efficient on-chip amplification [9].

One of the most likely candidates to replace the EDFA in the future is the SOA. At present, the SOA occupies only about 10% of the market, a trend highly likely to change in the future for many reasons. For example, SOAs are increasingly used in niche applications such as data centre interconnects [10] and in hybrid systems that combine EDFAs and Raman amplifiers to extend reach and bandwidth [11]. Unlike EDFAs, SOAs can provide amplification across the O-band (1310 nm), the E-band, and even into the visible spectrum, making them highly suitable for short-reach and silicon photonics applications [12]. Their small footprint and integration capabilities are particularly advantageous, since SOAs can be monolithically integrated with lasers, modulators, and detectors on a single chip—an essential feature for co-packaged optics and future photonic

interconnects [13]. Being already compact and chip-scale, SOAs are also viewed as promising candidates for nanophotonics [14] and quantum communication systems [15], where ultra-compact and low-power amplification is critical. Also, their ultrafast gain dynamics enable many applications in optical switching and high-speed signal processing [16]. Nevertheless, SOAs currently face challenges such as relatively higher noise figures (5 to 8 dB, compared to ~4 dB for EDFAs) and nonlinear effects like cross-gain modulation, which limit their effectiveness in long-haul transmission [17]. With continuous advances in fabrication techniques and the growing demand for miniaturization, SOAs are expected to dominate short-reach applications, and potentially challenge EDFAs in future long-haul networks [18].

Moreover, SOAs are not only compact amplifiers but also versatile functional devices due to their nonlinear gain saturation, enabling applications such as wavelength conversion and regeneration [19]. Since SOAs are chip-based devices only a few millimeters long, they are much smaller than EDFAs, which require several meters of doped fibre [2]. Their fast response time further enhances their role in next-generation optical networks [20] and their integration capabilities [21] make SOAs ideal for various optical signal processing tasks—including optical switching [22], fast four-wave mixing (FWM) [23], and signal regeneration [24]. Additionally, SOAs play a vital role in modern optical packet switching systems [25], enabling high-speed data switching and routing in next-generation network architectures [26]. Their ability to amplify and process optical packets is instrumental in ensuring efficient data transmission and routing in these advanced systems [27]. The most fundamental function of an SOA is to boost signals all-optically—such as serving as an in-line all-optical regenerator (2R/3R) or as a pre-amplifier [28]. SOAs are currently essential for maintaining signal integrity in short-range optical communication systems like MANs and LANs, where they amplify over relatively short distances [29], [30]. Due to ever-increasing data internet traffic, and hence the need to avoid bottlenecks, the SOA is increasingly becoming integrated in wavelength conversion functions [31]. This is internally facilitated through non-linear optical effects; such as cross-gain modulation (XGM) [32], cross-phase modulation (CPM) [33] and FWM [34]. SOAs can also perform optical logic operations such as AND, OR, and NOT, using nonlinear interactions and carrier dynamics [35] and perform pulse reshaping [16, 24, 32].

Interestingly, SOAs can also act as broadband light sources by utilizing their amplified spontaneous emission (ASE), useful in applications like optical sensing and component testing [36]. They can also act as intensity noise suppressors when saturated to a certain degree - very useful in spectrum-sliced systems. For example, novel work done in [37] achieved FWM from a total ASE source in an SOA for the first time (both pump and probe ASE were spectrally sliced from a single broadband source). Although decreasing the gain as a direct consequence of higher input power, the saturation effects of the SOA considerably reduced the measured relative-intensity noise (RIN) in the output FWM signal. Work done since with ASE FWM has improved the technique and practically eliminated polarization effects from the SOA when converting wavelength in such systems [38].

This paper reviews how the SOA device has changed over the years and its strong potential to dominate in future optical systems. Section 2 introduces the scope of the device and application ideas. Section 3 reviews the theory behind the practical workings of the SOA. Section 4 looks at changes in manufacturing trends over the years. Section 5 reviews former (historical), current (modern), and future (emerging) roles in photonic and telecommunication systems. Finally, conclusions are made in Section 6.

SCOPE OF THE DEVICE

The SOA these days has become an essential component in photonics and optical communication systems. As mentioned previously, the device amplifies optical signals directly without the need to convert them to electrical signals (all-optical), making it ideal for high-speed, high-bandwidth point-to-point systems, such as signal amplification in C-band dense wavelength divisional multiplexed networks (DWDM) [39]. Their dual role as amplifiers and all-optical switches also makes them suitable for complex network operations, such as routing and signal regeneration [19]. Table 1 shows the key steps in the burgeoning evolution of the device over time: from initial concepts gained using the semi-diode laser without feedback in the 1970s to present day deployment in quantum communication and AI-optimized telecom and datacenter systems.

TABLE 1 Timeline of Developments in SOAs

Decade	Development Stage	Key Innovations	Applications & Impact	Refs
1970s	concept & early research	initial proposals of optical amplification in semiconductors	mostly theoretical interest; foundational work on gain mechanisms	[40], [41]
1980s	first demonstrations	first practical demonstrations of optical gain in semiconductors	SOA first seen as potential alternatives to EDFAs in integrated photonics	[42], [43]
1990s	commercialization begins	**INTRODUCTION** of traveling-wave SOAs (TWSOAs), introduction of quantum-well structures	fibre optic communication systems - signal regeneration and wavelength conversion	[44], [45]
2000s	performance enhancement	quantum-dot SOAs (QD-SOAs), polarization-insensitive designs, reduced noise figures	metro and long-haul networks, all-optical signal processing	[46], [47], [48]
2010s	integration & miniaturization	integration with photonic integrated circuits (PICs), hybrid and monolithic integration	on-chip optical networks, all-optical logic and computing	[49], [50]
2020s	advanced materials & AI-driven design	use of graphene, InP, and novel nanomaterials, AI/ML for design optimization	quantum communication, AI-optimized telecom and datacenter systems	[51], [52]
Future	ultra-fast, quantum & green photonics	ultrafast, low-energy SOAs, spintronic and quantum SOAs	quantum networks, sustainable photonic systems	[53], [54]

From table 1, it is worth highlighting that before the advent of QD-SOAs, conventional semiconductor optical amplifiers (using bulk materials or quantum wells) suffered from slow gain recovery (limiting data speeds), temperature sensitivity (requiring coolers) and high signal distortion. The development of Quantum Dot SOAs (late 1990s/early 2000s) leveraged 3D quantum confinement to enable ultrafast operation (femtosecond gain recovery), temperature-insensitive performance, lower noise and reduced distortion [46 – 48]. This breakthrough transformed optical communications, enabling high-speed (>160 Gb/s) signal processing, energy-efficient photonic integrated circuits and robust amplifiers for next-gen networks—establishing QDs as a cornerstone of modern photonics.

Another pivotal role of SOAs is in Photonic Integrated Circuits (PICs). Due to their compact size and compatibility with semiconductor processes, SOAs can more easily be integrated with lasers, modulators and detectors on-chip [25, 55]. This allows for the development of more compact, power-efficient and higher-performance optical systems for data centers and high-speed computing. This contrasts sharply with the bulky other types of amplifiers previously mentioned, which can only be used for gain of course [39].

SOAs have now also entered the realms of optical sensing and biomedical imaging systems. For example, in optical coherence tomography (OCT) [56], it has been shown that the SOAs broad bandwidth, compactness, ruggedness, electrically pumped advantages, tunable gain capability and cost effectiveness were all factors instrumental in providing the necessary broadband light for high-resolution OCT imaging. Of course, SOAs themselves are not classical sensors like photodiodes or strain gauges - they do not directly measure temperature, pressure, chemicals, etc. However, because they are very sensitive to changes in their environment (like temperature, input optical power, bias current, and even surrounding refractive index), these sensitivities can be used to detect changes [57]. In this work, the SOA acted as the active element enabling a fibre ring laser to function effectively as a dynamic strain sensor, where strain-induced changes modulated the laser output detected through the arrayed waveguide grating demodulator.

However, despite many advantages, SOAs still presently face challenges like high noise figures, polarization sensitivity and gain saturation [47]. Many SOA polarization diversity schemes have recently been reported in the literature [58–61]. These modern works all produced polarization robustness, wide spectral gain, ultrafast nonlinear dynamics with energy-efficiency. Current research on advanced SOA designs, such as quantum-dot and quantum-dash structures, is now overcoming the aforementioned issues and extending performance [34]. This study demonstrated that quantum dot semiconductor optical amplifiers (QD-SOAs) effectively enabled four-wave mixing (FWM) with high conversion efficiency and broad wavelength tunability. Thanks to the unique properties of quantum dots, the SOA exhibited improved nonlinear performance compared to conventional devices; such as wider wavelength conversion range and reduced signal distortion. These results highlighted the potential of QD-SOAs as compact, high-performance components for all-optical wavelength conversion and signal processing in next-generation optical communication systems.

In summary, the scope of the SOA is highly multidisciplinary, enhancing data transmission and enabling complex operations in integrated photonics. Their continued development is critical to future next-generation optical technologies.

THEORY

The theory of SOAs is based on semiconductor physics and optical wave propagation, and has been well documented [42]. Similar to laser diodes, SOAs use a semiconductor gain medium but are designed to amplify light without generating coherent light. They utilize stimulated emission, where incoming photons stimulate excited electrons to drop energy levels, releasing more photons in the same direction and phase [39]. The active region, often made of Indium Gallium Arsenide Phosphide (InGaAsP) or Indium Aluminum Gallium Arsenide (InAlGaAs), becomes optically active when a forward bias injects carriers [55]. Light is confined through waveguides in this active region. The achieved gain depends on the injected current, carrier density, input power and wavelength. At high powers, SOAs experience gain saturation due to carrier depletion [19]. This mechanism can be seen in figure 1:

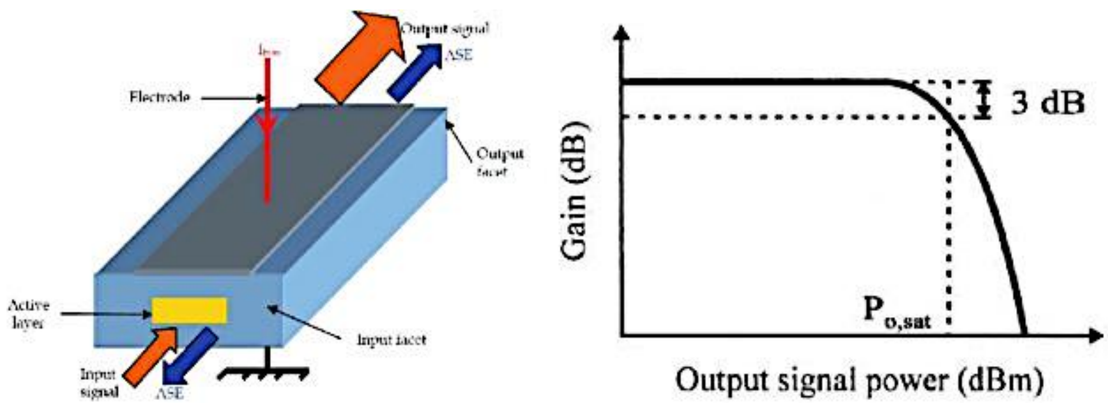

Fig. 1 SOA gain mechanism [62]

This figure illustrates the key characteristics of SOA gain dynamics and signal behavior. It highlights the output signal, which includes Amplified Spontaneous Emission (ASE) and electrode-controlled left/right inputs, as well as the output target, comprising the input facet, active layer, input signal, and ASE. The diagram also presents performance metrics such as gain (dB), output power (dBm) and saturation effects. Together, these elements depict how an SOA amplifies optical signals while managing ASE noise, gain saturation, and input-output power relationships—critical factors in optical communication and signal processing applications.

The theoretical gain of a SOA is typically given by $G = \exp(\Gamma \cdot g \cdot L)$, where Γ is the optical confinement factor, g is the material gain coefficient (in cm^{-1}), and L is the length of the active region (in cm) [42]. Under small-signal conditions, where input power is low, the gain simplifies to $G_0 = \exp(g_0 \cdot L)$, with g_0 representing the unsaturated material gain. At higher input powers, gain saturation occurs and the gain becomes power-dependent, following $G(P) = G_0 / (1 + P_{in} / P_{sat})$, where $G(P)$ represents the saturated gain of the semiconductor optical amplifier (SOA) as a function of input power, P_{in} is the input optical power and P_{sat} is the saturation power. Typical SOAs exhibit gains in the range of 10 to 40 dB, with gain coefficients from 100 to 2000 cm^{-1} and device lengths between 200 μm and 2 mm. This SOA gain mathematics is shown in figure 2:

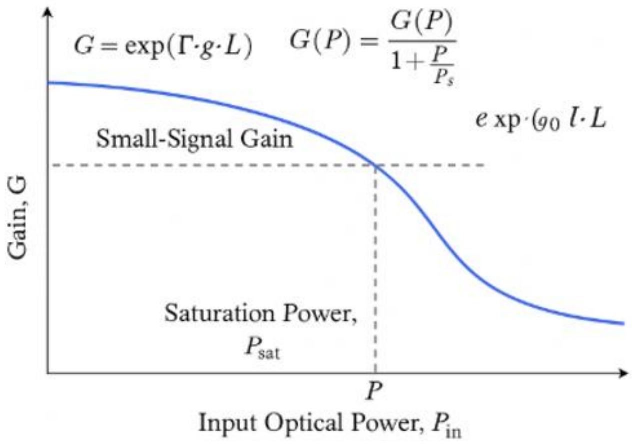

Fig. 2 Gain versus input optical power in a semiconductor optical amplifier (SOA), illustrating small-signal gain, gain saturation, and the typical exponential gain behaviour [42].

This mathematical framework forms the basis for understanding SOA performance in both linear and nonlinear regimes, and is essential for the design and optimization of optical communication and signal processing systems.

Previously mentioned nonlinear effects - like XGM, XPM and FWM - arise from carrier dynamics within the SOA and are useful for wavelength conversion [20] and switching [22]. In [22], the authors presented a design for a compact and energy-efficient optical switch based on SOAs. The nonlinear gain and fast carrier dynamics of the SOA were used to achieve reconfigurability with low switching power. The proposed switch demonstrated sub-nanosecond switching times and small footprint, making it suitable for integration into optical networks where rapid, low-power switching is essential. This work highlighted the potential of SOAs as versatile components for scalable, high-speed photonic switching applications.

A summary of SOA non-linearities is shown in table 2. They are primarily due to its unique gain saturation characteristics, unlike the other amplifier types, rendering the device highly versatile in practical terms.

TABLE 2 Summary of SOA Non-Linear Applications

Nonlinear Application	Description	Key Features/how	Applications	**REFERENCES**
all-optical switching	SOAs enable fast switching without converting signals to electrical form	saturation of the amplifier's gain with high input power	optical switching networks	S. J. Savory *et al.*, 2004 [63] G. R. M. *et al.*, 2001 [64]
optical regeneration	SOAs can regenerate signals by reshaping degraded optical pulses	non-linear gain recovery due to power saturation	long-distance communication	M. A. T. F. *et al.*, 2005 [65] R. P. Taylor *et al.*, 2009 [66]
wavelength conversion	SOAs can convert signals to a different wavelength using nonlinear effects	cross-phase modulation (XPM) and four-wave mixing (FWM)	wavelength-division multiplexing (WDM) systems	F. S. R. *et al.*, 2003 [67] M. A. I. *et al.*, 2008 [68]
four-wave mixing (FWM)	interaction of multiple optical signals in an SOA to generate new frequencies	non-linear interaction between input signals	generation of new optical channels, signal processing	P. R. K. *et al.*, 2006 [69] A. D. Ellis *et al.*, 2009 [70]
optical parametric amplification (OPA)	SOAs can be used in optical parametric	parametric amplification with signal conversion	signal amplification in	P. R. Sharpe *et al.*, 2010 ([71]

	amplifiers to amplify weak signals		fibre optic communication	T. R. Chou *et al.*, 2006 [72]
cross-phase modulation (XPM)	non-linear effect where the phase of one signal is modulated by another signal.	intensity-dependent phase shift, dependent on signal power	optical pulse shaping, signal processing	J. P. Yao *et al.*, 2011 [73] C. D. M. *et al.*, 2005 [74]
self-phase modulation (SPM)	a single optical signal experiences a phase shift due to its own intensity	intensity-dependent phase shift in the SOA medium	pulse broadening, soliton generation	C. M. DeAngelis *et al.*, 2013 ([75] J. L. Silva *et al.*, 2007 [76]
supercontinuum generation	SOAs can generate a broad spectrum from a narrowband source using nonlinearities	non-linear mixing, Raman scattering, and self-phase modulation	spectral broadening for metrology, medical imaging	A. P. L. *et al.*, 2010 [77] S. M. *et al.*, 2006 [78]
optical logic gates	SOAs can implement basic logic functions for optical computing	non-linear switching effects such as AND, OR, and XOR gates	optical computing, signal processing	S. S. Banerjee *et al.*, 2005 [79] P. C. G. *et al.*, 2004 [80]
brillouin scattering	SOAs can be used for Brillouin scattering applications, leading to pulse compression or filtering	stimulated brillouin scattering (SBS) effect	pulse shaping, noise filtering	J. T. F. *et al.*, 2008 [81] K. S. *et al.*, 2012 [82]
non-linear distortion	the nonlinear characteristics of SOAs can induce distortions	harmonic generation, intermodulation	signal distortion in optical communication systems	P. D. A. *et al.*, 2011, [83] N. Essiambre. *et al.*, 2013 [84]

Table 2 shows that SOAs leverage their inherent nonlinearities to enable a diverse range of advanced photonic functions beyond simple amplification. Key applications include all-optical switching and logic gates (utilizing gain saturation for ultrafast signal control), optical regeneration (exploiting nonlinear gain recovery to reshape degraded pulses), and wavelength conversion (achieved via cross-phase modulation (XPM) or four-wave mixing (FWM)). SOAs are also fundamental for FWM and optical parametric amplification (OPA) to generate new frequencies or amplify signals, while XPM and self-phase modulation (SPM) facilitate critical signal processing tasks like pulse shaping and soliton generation. Furthermore, their nonlinear properties enable supercontinuum generation for broad-spectrum light sources and Brillouin scattering applications for pulse compression and filtering, though they can also introduce undesirable non-linear distortion in communication systems through effects like harmonic generation. Collectively, these capabilities make SOAs vital components in optical switching networks, wavelength-division multiplexing (WDM) systems, long-haul communication, optical computing, and specialized areas like metrology.

One of the most interesting and promising techniques for the future from SOA non-linearity phenomena from table 2 is four-wave mixing (FWM), which has been highly referenced in the literature [25], [34], [37], [44], [69], [70]. In [34], by optimizing the SOA design and operating parameters, the authors achieved enhanced FWM efficiency with a wide conversion bandwidth and low power consumption; a conversion bandwidth of 10.8 nm (approximately 1.35 THz in frequency) with a peak conversion efficiency of –6.7 dB was reported here. The principle of FWM is the non-linear optical interaction within the SOA which generates new wavelengths from the interaction of two or more input waves [44]. This is shown in figure 3:

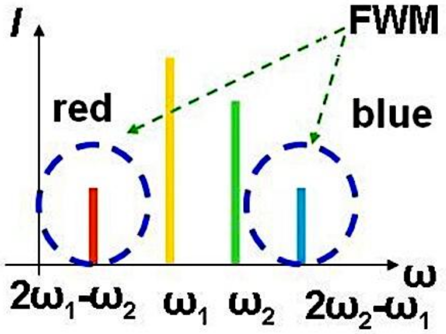

Fig. 3 SOA FWM mechanism (44)

This figure shows four-wave mixing (FWM) in a nonlinear medium, such as an SOA, where two input frequencies (ω_1 and ω_2, represented by *red* and *blue* lines) interact to generate two new frequencies through nonlinear optical processes. The labels "$2\omega_1 - \omega_2$" and "$2\omega_2 - \omega_1$" indicate the resulting FWM products, which are created by combinations of the original frequencies arising from nonlinear interactions. Normally only one sideband is used for the wavelength conversion. The side-bands are generated through the third-order susceptibility ($\chi^{(3)}$), mediated by carrier density modulation and gain nonlinearities. The FWM power P_4 at $\omega_4 = 2\omega_1 - \omega_2$ scales as:

$$P_4 \propto |\chi^{(3)}|^2 P_1^2 P_2 e^{(\Gamma g - \alpha)L}$$

where:

Γ = confinement factor

g = Material gain

α = loss coefficient

and L = SOA length

FWM efficiency depends on phase matching ($\Delta k \approx 0$) and is degraded by carrier depletion and gain saturation, evident in the figure's weaker FWM tones [42]. The process enables wavelength conversion but is inherently power-limited due to the SOA's nonlinear dynamics, with $\chi^{(3)}$ peaking near the gain spectrum but suppressed at high intensities.

SOA FWM has quite recently been shown to give best spectral efficiency and bandwidth of wavelength conversion [86]. Here, using a QD-SOA, the authors exploited the inhomogeneous broadening in quantum dots, enabling > 100 nm wavelength conversion bandwidth (vs. ~10–20 nm in bulk SOAs) over the C and L bands, together with <−10 dB conversion efficiency. Figure 4 shows the principal output of their work:

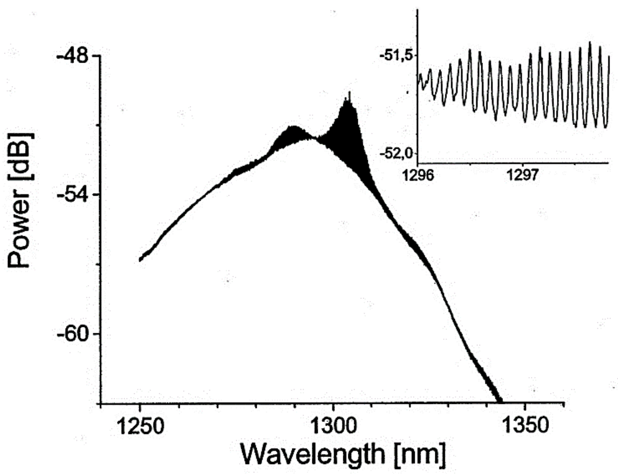

Fig. 4 ASE spectrum of the QD-SOA showing >100 nm bandwidth from C to L band, indicating inhomogeneous broadening. [86]

SOA FWM also preserves phase and amplitude (good for advanced modulation formats) and allows wavelength conversion in both directions (symmetrical). In [87], the authors demonstrated that the SOA effectively preserved both the phase and amplitude of the optical signals, crucial for accurately converting advanced modulation formats such as quadrature phase-shift keying (QPSK) and polarization-multiplexed QPSK signals. This research also highlighted the ability of SOA-based FWM to achieve symmetrical wavelength conversion, facilitating bidirectional communication in optical networks. The SOA previous sensitivity to polarization effects are these days increasingly becoming diminished [88]. In this very recent work, the authors presented the design, fabrication and characterization of an SOA optimized for the O-band (1310–1350 nm) with low polarization sensitivity - less than 1 dB polarization dependent gain (PDG) over a 25 nm bandwidth from 1312 nm to 1337 nm, suitable for integration into large-scale photonic integrated circuits (PICs). Also, in [89], a novel scheme for wavelength conversion of orthogonal frequency division multiplexing (OFDM) signals was introduced. This scheme leveraged FWM in an SOA to achieve cost efficiency, polarization insensitivity and wide tunability. While the paper emphasizes the polarization-insensitive nature of the proposed scheme, it did not provide specific quantitative metrics; such as polarization-dependent gain (PDG) or polarization-dependent loss (PDL), to measure the degree of polarization sensitivity. However, the authors supported their claims through analytical results and numerical simulations. Speed will also be even more important in the future: the fastest SOA FWM ever achieved to date is 1 Tb/s (by simulation) [90] and 200 Gb/s (practically using a QD-SOA) [91]. Figure 5 shows these results achieved practically:

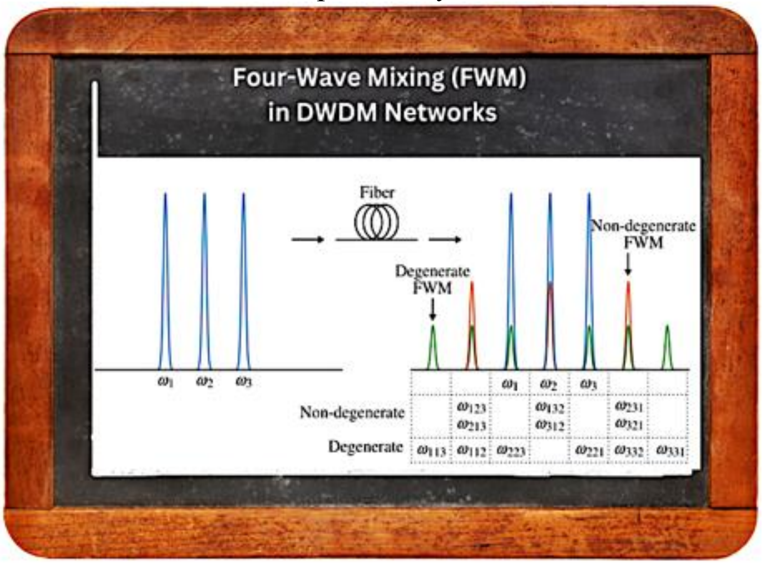

Fig. 5 Spectral output of pump, signal, and FWM-generated idler from a QD-SOA at ~200 Gb/s wavelength conversion, demonstrating efficient conversion with preserved modulation format and phase integrity [91]

This work experimentally demonstrated error-free 200 Gb/s wavelength conversion using four-wave mixing (FWM) in a quantum-dot semiconductor optical amplifier (QD-SOA), achieving record efficiency (-8.2 dB) while preserving phase integrity. By leveraging the ultrafast carrier dynamics of quantum dots, the authors showed high-quality NRZ-OOK signal conversion with clear eye diagrams and low power penalty, validated through bit-error-rate (BER) measurements. Published in IEEE Photonics Technology Letters, this study represented a significant advancement in all-optical signal processing, proving QD-SOAs as viable devices for ultrahigh-speed optical communication systems.

For all these reasons – the technique of FWM in an SOA has one of the highest potentials for future wavelength conversion in current high-speed and coherent systems and in phase-sensitive applications (for example: QPSK, 16-QAM [92]).

MANUFACTURING TRENDS

The evolution of SOA manufacturing has been marked by significant advancements in materials (e.g., GaAs to quantum dots), performance (high gain, low noise, polarization insensitivity), and integration (compact PICs for space and telecom). Modern SOAs now offer ultrafast switching (>160 Gbps), radiation-hardened designs, and miniaturization, with Asia dominating production. Leading manufacturers like Coherent Corp. and innovators such as Innolume push the limits in speed (640 Gbps QD-SOAs) and functionality, while cost and weight advantages over EDFAs solidify SOAs' role in next-gen optical systems.

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a) Evolution

The evolution of the SOA over the years can be described under certain sections:

i) material innovations - early SOA devices were based on GaAs homojunctions operating at low temperatures before they began to utilize materials like aluminum gallium arsenide (AlGaAs), operating around 830 nm [93]. The introduction of indium phosphide (InP) and indium gallium arsenide phosphide (InGaAsP) materials then enabled operation in the 1.3 µm and 1.5 µm wavelength windows [94], a basic window requirement for fibre-optic communications. Evolving then came the incorporation of quantum dots (QDs), which has enhanced SOA performance - achieving faster gain saturation response times and improved noise suppression [95].

ii) enhanced performance metrics - advancements then led to SOAs with gains exceeding 20 dB and saturation output powers suitable for high-speed data transmission [96]. This paper reported on an SOA with a massive 35 dB gain and 14 dBm saturation output power running at potentially 100 Gb/s. Implementing strained quantum wells and optimized waveguide structures then resulted in lower noise figures, thereby enhancing signal quality [97]. Additionally, design improvements, such as symmetrical waveguide structures and tensile-strained active layers, have minimized polarization-dependent gain, making SOAs more versatile in various applications [98]. This work achieved a polarization-dependent gain of < 0.5 dB (across the C-band) and a wide gain bandwidth of > 50 nm across the C+L band while maintaining complete polarization insensitivity. The principal results from this work are shown in figure 6:

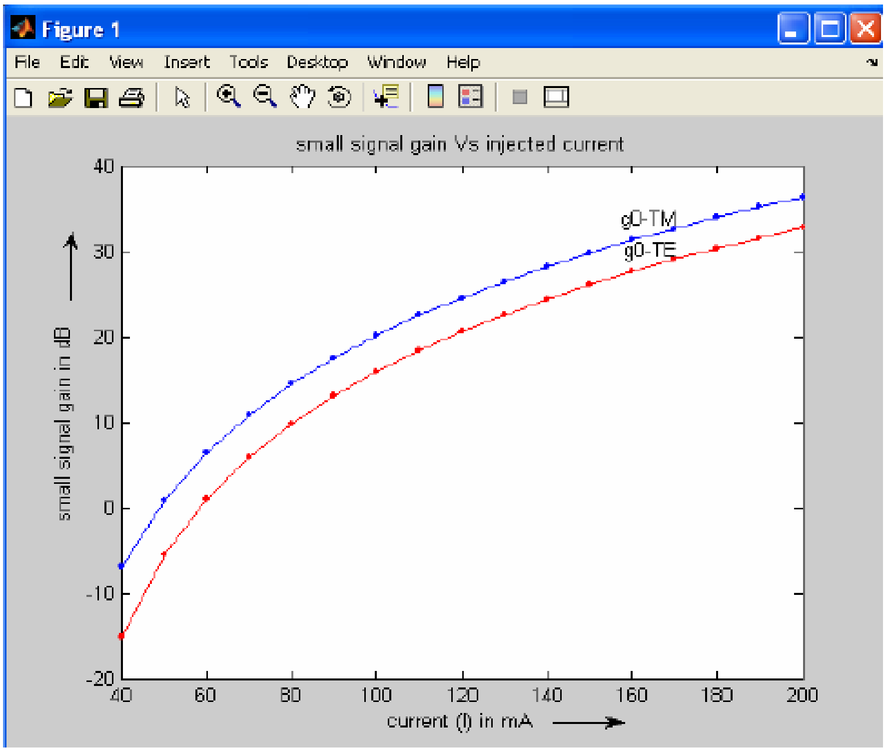

Fig. 6 Small-signal gain spectra for TE and TM polarization modes in the optimized SOA, showing PDG < 0.5 dB across the C+L band [98]

This figure plots the small-signal gain for transverse-electric (TE) and transverse-magnetic (TM) modes across the C+L band, clearly demonstrating polarization-dependent gain (PDG) below 0.5 dB, thus confirming the effective polarization insensitivity as described in the reference.

iii) integration and miniaturization - recent advances in photonic integration have incorporated SOAs into photonic integrated circuits (PICs), such as InP-on-silicon membrane platforms, enabling compact and energy-efficient amplification solutions [99]. This integration facilitates seamless interfacing with other optical components, enabling sophisticated communication systems [100]. A 2022 report from NASA demonstrated radiation-hardened SOA-based PICs with <1 dB polarization sensitivity, capable of operating across -40°C to 85°C and sustaining up to 100 krad of total ionizing dose. These robust PICs maintained high bandwidth under extreme conditions, enabling high-speed optical systems to replace conventional RF technology in deep-space missions such as Mars exploration. From this work, figure 7 shows the SOA-PIC gain stability under cumulative radiation exposure.

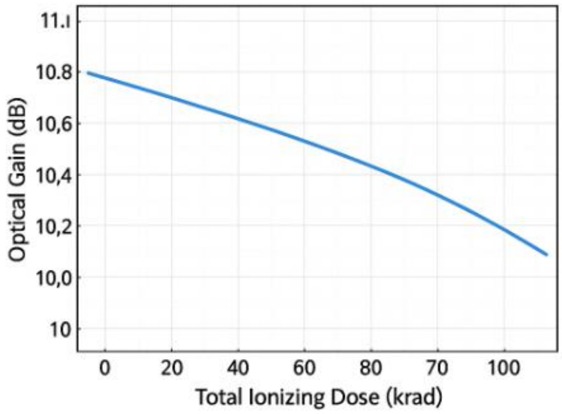

Fig. 7 Optical gain stability of a radiation-hardened SOA-PIC under ionizing radiation up to ~100 krad, showing <1 dB degradation—demonstrating robustness for space applications [100]

This figure illustrates the optical gain stability of a radiation-hardened SOA-based photonic integrated circuit (PIC) subjected to ionizing radiation up to ~100 krad. The gain shows less than 1 dB degradation, confirming the PIC's resilience and suitability for harsh space environments, as reported in the 2022 NASA study.

iv) advanced functionalities - beyond amplification, modern SOAs have been engineered for ultra-fast switching and signal processing capabilities [101]. This thesis demonstrated sub-nanosecond (≤ 500 ps) all-optical switching in SOAs, enabling > 40 Gbps operation with low penalty (<1 dB), while also developing a numerical model to optimize carrier dynamics, achieving a > 20 dB extinction ratio and < 10^{-10} BER for WDM applications. By exploiting rapid gain modulation, SOAs can perform all-optical signal processing tasks, revolutionizing data routing and switching in optical networks [102]. Here, the authors theoretically and experimentally analyzed the ultimate speed limit of a quantum-dot SOA for all-optical switching. They successfully demonstrated picosecond-scale (1–10 ps) recovery times via ultrafast carrier dynamics engineering, while identifying nonlinear gain compression and phase noise as critical bottlenecks for THz-rate operation. Their models showed that SOAs could support > 160 Gbps switching in optimized configurations, paving the way for terabit-scale photonic signal processing. The principal output of their work is shown in figure 8:

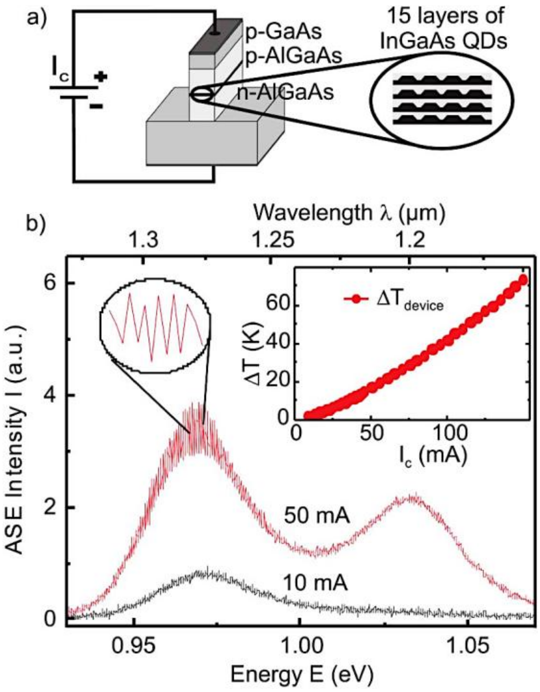

Fig. 8 Time-resolved pump–probe measurement of gain (or phase) recovery in a quantum-dot SOA, showing sub-10 ps recovery and demonstrating ultrafast all-optical switching capabilities (>160 Gbps potential) [102]

This pump–probe measurement from a QD-SOA illustrates ultrafast all-optical switching behavior: the gain (and phase) recovers on a picosecond scale (approximately 1–10 ps). Such time-resolved traces confirm sub-

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nanosecond switching capabilities with large extinction ratios and support the theoretical projections of >160 Gbps to terabit-per-second performance.

b) Present Day SOA Manufacturing

Today, several Semiconductor Optical Amplifier (SOA) models have gained prominence in the industry due to their performance, versatility, and integration capabilities. Here are some of the most widely adopted SOA models currently in use:

(i) The 14BF 290 SOA by RPMC Lasers [103], shown in figure 9, is a high-power semiconductor optical amplifier operating at 1310 nm, offering up to 450 mW output power and approximately 30 dB gain, packaged in a 14-pin butterfly module with TEC, thermistor, and photodiode.

Fig. 9 14BF-290 RPMC Lasers High Power SOA [103]

It is optimized for O-band optical communication, LIDAR, and sensing applications requiring high stability,polarization-maintaining fibre, and robust thermal management.

(ii) InPhenix O-Band SOAs [104] currently deliver solid gain, respectable output power, low noise, and polarization independence—packaged in robust, integration-ready modules, making them a strong choice for modern O band optical systems. The currently available device is shown in figure 10:

Fig. 10 InPhenix's 1310nm O-Band SOA [104]

(i) AeroDIODE currently offer a SOA for CW or pulsed operation in the range from 750 to 1550 nm [105], as shown in figure 11:

Fig. 11 AeroDIODE SOA [105]

(ii) Box Optronics currently offer the 1310nm 10dBm SOA Semiconductor Optical Amplifier SM Butterfly [106], shown in figure 12

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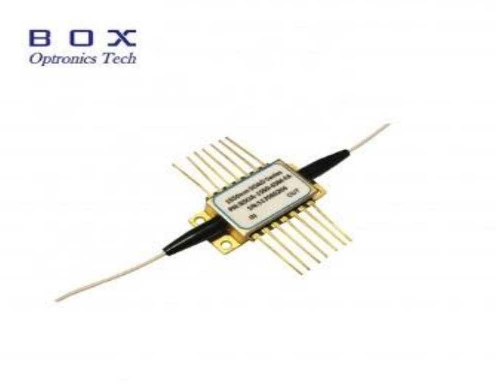

Fig. 12 1310nm 10dBm SOA Semiconductor Optical Amplifier SM Butterfly [106]

(iii) Thorlabs [107] currently offer SOAs operating from 780 to 1700 nm. Figure 13 shows one at 1700 nm.

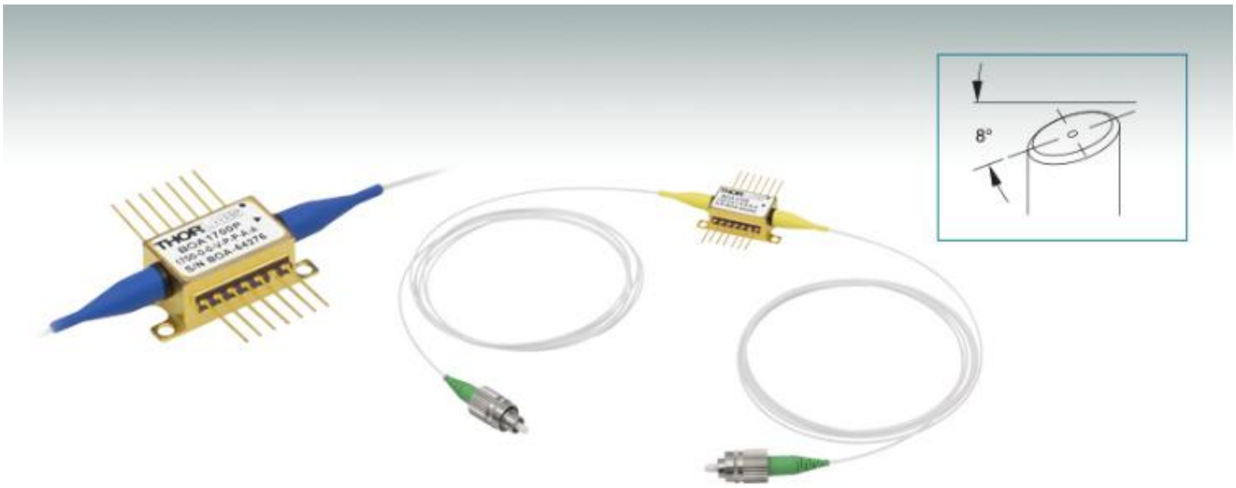

Fig. 13 Thorlabs booster SOA operating at 1700 nm [107]

As of 2025, Coherent Corp. stands out as the world's largest manufacturer of SOAs [108], with the average production time for a commercial SOA currently typically ranging from 8 to 16 weeks, depending on complexity and supplier logistics. Currently Asia dominates the global Semiconductor Optical Amplifier (SOA) market, accounting for approximately 70–85% of production and sales (by volume). The smallest commercially available SOA currently on the market is the Anritsu AA3T115CY [109], a 1310 nm chip carrier type SOA. This ultra-compact device is specifically designed for integration into miniaturized optical transceivers and photonic integrated circuits (PICs), making it ideal for applications where space is at a premium. The dimensions of this particular device are: 3.5 mm × 2.5 mm × 0.9 mm (making it the smallest commercial SOA as of 2024). Interestingly, on average the EDFA is 2–10 times heavier than an average SOA, depending on power and packaging [4]. If weight is a critical factor (e.g., in aerospace or portable systems), then SOAs are preferred [26]. However, for high-gain, low-noise applications (e.g., telecom), EDFAs still dominate despite their much higher weight [6]. Regarding price, the current world average price of a single stand-alone SOA (as of 2025) is estimated to be around 3.5k US dollars [103 – 107]. On average, an SOA costs 5–10× less than an EDFA [108]. Regarding composition – one key factor, particularly in light of their manufacture these days, is that EDFAs totally depend on rare-earth-doped fibres for amplification [4], whilst SOAs leverage semiconductor bandgap engineering, avoiding rare-earth materials entirely [42,93].

Regarding speed, the fastest semiconductor optical amplifiers (SOAs) demonstrated to date leverage quantum dot (QD) technology to achieve unprecedented speeds [95]. Recent breakthroughs include p-doped InAs/InP QD-SOAs achieving 640 Gbps all-optical switching with 0.3 ps carrier recovery, enabled by ultrafast carrier depletion in optimized nanostructures [109]. For direct amplification, 400 Gbps operation with >25 dB gain has been demonstrated in QD-SOAs, showcasing their potential for high-speed signal regeneration [110]. Theoretical work suggests even higher speeds are attainable, with plasmonic-enhanced SOAs incorporating graphene predicted to reach 1.28 Tbps due to sub-picosecond nonlinear responses [111]. Commercial offerings

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like II-VI's QD-SOAs now support 320 Gbps signal processing [112], while Lumentum's quantum well (QW) SOAs deliver 200 Gbps PAM-4 amplification [113]. The primary limitations remain gain saturation at ultrahigh speeds and fabrication challenges for plasmonic hybrids. At the time of writing (2025), one of the fastest commercially available SOAs is the Innolume SOA-1110-40-YYY-FA [114], featuring a >100 GHz bandwidth and < 5 ps rise time, enabled by quantum-dot technology for ultrafast signal processing. Designed for high-speed applications like coherent LiDAR and quantum communications, it delivers ~20–25 dB gain and 40 mW output power in the 1060–1120 nm range. While its premium performance comes at a cost (~$15k–$25k), it's a top-tier choice for systems requiring THz-class optical amplification beyond standard SOAs. The device is shown in figure 14:

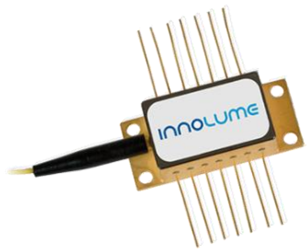

Fig. 14 Innolume SOA-1110-40-YYY-FA [114]

APPLICATIONS

a. Former Applications

The first studies on SOAs were conducted around the time of the invention of the semiconductor laser in the 1960s, with early devices based on GaAs homojunctions operating at low temperatures [93]. The arrival of double heterostructure devices spurred further investigation into the use of SOAs in optical communication systems. Zeidler and Personick [115] conducted early work on SOAs in the 1970s, laying the groundwork for future developments. In the 1980s and early 1990s, the SOA continued to find limited but important roles - mainly in experimental set-ups and niche applications where their compactness, electrical control and integration potential began to offer unique advantages over bulkier fibre-based EDFAs [116]. However, the first real key breakthrough development SOA paper was published in 1982 [117]. Simon's 1983 study on traveling-wave semiconductor laser amplifiers (TW-SLAs) revealed that these devices exhibit significant polarization-dependent gain, with TM-polarized signals receiving higher amplification than TE-polarized ones. Although TW-SLAs were designed to reduce feedback compared to Fabry-Pérot structures, Simon's measurements demonstrated that polarization sensitivity remained a critical challenge. This finding underscored the need for polarization control in optical systems and laid the groundwork for the development of polarization-insensitive SOAs in subsequent years [118]. Figure 15 shows the principal output of [117] :

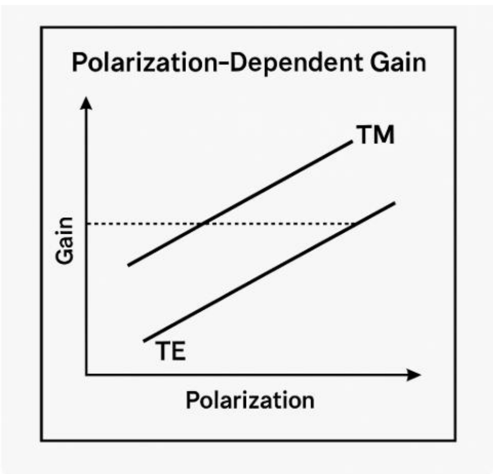

Fig. 15 Polarization-dependent gain in a traveling-wave semiconductor laser amplifier (TW-SLA), illustrating higher gain for TM-polarized light compared to TE-polarized light. The gain disparity highlights the inherent polarization sensitivity of early SOA designs [117].

This figure shows a comparison of gain for TE and TM polarized light in a traveling-wave semiconductor laser amplifier (TW-SLA). The vertical axis represents optical gain, while the horizontal axis denotes polarization. Two separate lines illustrate that TM polarization experiences higher gain than TE, clearly demonstrating the **amplifier's** polarization sensitivity. A dotted reference line emphasizes the gain disparity, highlighting a key limitation in early SOA designs for polarization-diverse systems.

b. Current Applications

Modern semiconductor optical amplifiers (SOAs) have significantly benefited from advancements in materials and fabrication techniques, as detailed in Section 4. Today, they are increasingly employed in wavelength-division multiplexing (WDM) systems for signal amplification, wavelength conversion, and optical switching [119]. Their integration into photonic integrated circuits (PICs) allows for compact, chip-level systems combining SOAs with lasers and detectors [120]. SOAs are emerging as a preferred solution for all-optical signal processing, leveraging cross-gain modulation (XGM) [121], four-wave mixing (FWM) [122], and signal regeneration for high-speed data manipulation. Beyond telecommunications, they are finding new applications in biomedical sensing and imaging, such as optical coherence tomography (OCT), where they enhance weak signal detection and reduce intensity noise. For example, in [123] an advanced swept-source design incorporated a booster SOA, placed outside the main swept laser cavity. Figure 16 shows the experimental set-up used here incorporating the BOA (booster SOA):

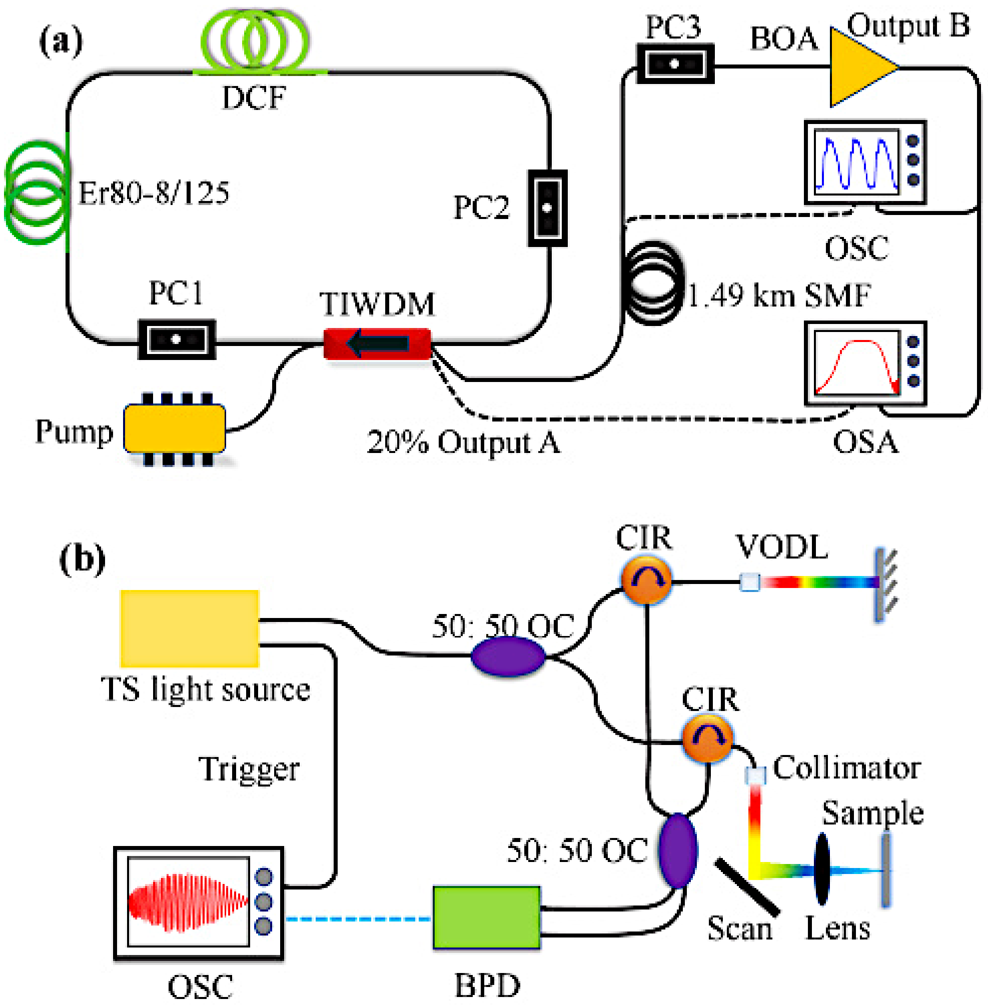

Fig. 16 experimental set-up used to incorporate a BOA (booster SOA) [123]

Panel (a) shows the system architecture, including a Fourier-domain mode-locked (FDML) laser followed by a booster SOA placed outside the laser cavity. This SOA serves two roles: amplifying the light and flattening the output spectrum. Panel (b) depicts how the optical bandpass filter selects and shapes a narrow spectral region during the sweep. The booster SOA, in combination with the filter and polarization control, enables a broad, flat, and coherent swept spectrum, which is essential for achieving high axial resolution in OCT imaging [123].

Another critical application is in Light Detection and Ranging (LiDAR) systems, where SOAs enable compact Doppler-ranging devices as well as high-resolution mapping arrays [124], [125]. For instance, frequency-modulated continuous-wave (FMCW) LiDAR, used in autonomous vehicles and drones, relies on SOAs to detect motion via the Doppler effect [126]. These systems also support cartography and industrial inspection applications [127]. Narrowband SOAs, often paired with distributed feedback (DFB) lasers, can deliver high output power (>20 mW), extending their effective range [128]. In parallel, SOAs have also been exploited in all-optical regeneration schemes, where quantum-dot SOAs provide improved signal reshaping and noise suppression, thereby enhancing transmission reach and system reliability [129].

In optical communications, SOAs are now integral to 100G CFP/CFP2 ER4 modules, where they amplify signals in the 1.3 μm band, enabling 40 km transmissions between data centers and mobile base stations [130]. Additionally, they serve as pre-amplifiers in long-haul systems, compensating for signal attenuation [16]. Theoretical modeling remains indispensable in SOA research, providing critical insights into their nonlinear and dynamic behavior—key to optimizing optical communication and signal processing systems. Early foundational work by Connelly established comprehensive models incorporating gain saturation, carrier rate equations, chirp, and amplified spontaneous emission (ASE), forming the basis for commercial simulation tools like VPIphotonics and OptiSystem [131], [132]. Connelly's dynamic model remains widely cited for its accuracy in predicting both steady-state and transient SOA performance. Building on this, his 2006 paper [132] shifted focus to steady-state modeling of SOAs under continuous-wave (CW) conditions. This model captured spatial variations of carrier density and optical fields along the SOA using coupled traveling-wave and rate equations. Although it omitted ultrafast effects like TPA or SHB, it provided a robust framework for analyzing gain saturation, ASE, and noise figure across a wide range of input powers and bias currents. This 2006 work complemented the earlier 2001 dynamic model by addressing static performance metrics critical for amplifier design, linking both works through a progression from time-domain to spatial-domain modeling for comprehensive SOA analysis. Figure 17 shows three of Connelly's simulations from his 2006 work:

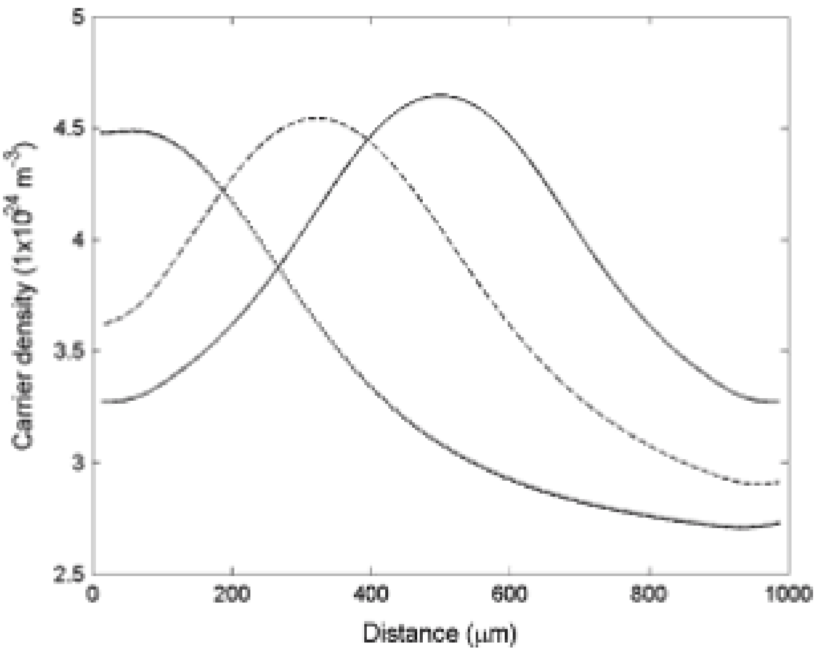

Fig. 17 Simulated carrier density spatial distributions for TM polarised signal input powers of −40 dBm (solid line), −10 dBm (dashed line) and 0 dBm (dotted line). The bias current and signal wavelength are 200 mA and 1550 nm, respectively. [132]

This figure illustrates how carrier density varies along the SOA for TM-polarized input powers of −40 dBm, −10 dBm, and 0 dBm. At low input power, carrier density remains high and centrally peaked due to minimal depletion. As input power increases, stimulated emission depletes carriers more significantly, especially near the input facet, leading to a reduced and flattened carrier profile. This highlights the impact of input power on gain saturation and SOA performance.

Further modelling contributions by Mecozzi, Antonelli, and Shtaif advanced further the understanding of nonlinear effects such as cross-phase modulation (XPM), FWM, and gain-induced phase distortions—essential

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for high-speed wavelength conversion and all-optical logic [133]. These models enabled practical implementations, as demonstrated by Durhuus *et al*. and Joergensen *et al*., who later applied theoretical insights to optimize SOAs in WDM systems [134, 135].

More recent modeling efforts support novel SOA architectures and functionalities. For example, Tang *et al*. has designed a wide-gain-bandwidth, polarization-insensitive SOA using tensile-strained quantum wells, validated through extensive simulations [136]. High-speed all-optical NOR gates have been modelled with improved extinction ratios [137], while Kotb *et al*. have simulated SOA-based header processors using carrier reservoir dynamics, highlighting the role of numerical tools in advancing optical logic [138]. Misra *et al*. further refined state-of-the-art models, incorporating ASE noise, gain dynamics, and saturation effects to bridge device physics with system-level integration [139].

Wang *et al*. demonstrated a breakthrough in Nature Photonics (2022) with an ultra-broadband MDM-SOA supporting 6 spatial modes, achieving 92% efficiency improvement, <0.5 dB modal crosstalk, and 3.2 dB noise figure across C+L bands (1520–1620 nm) through monolithic multi-core InP/InGaAsP integration, enabling high-density optical interconnects. [140]. Additionally, Wang *et al*. also leveraged mode-division multiplexing (MDM) modeling to achieve an 87% gain enhancement in SOAs, showcasing the potential for future efficiency improvements [141]. Collectively, these studies underscore that theoretical modeling is not merely supportive but foundational—driving innovation, optimizing performance, and enabling SOAs to meet the demands of both conventional and emerging photonic applications. The theory behind Wangs work in [141] is shown in figure 18:

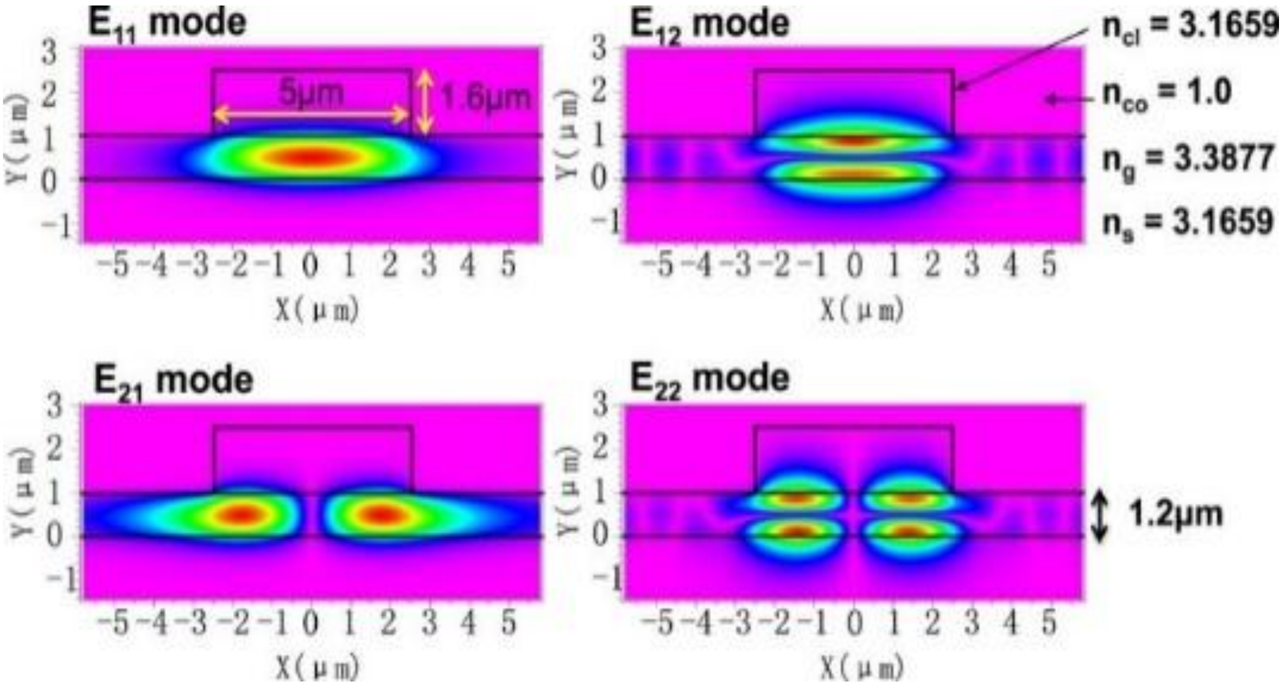

Fig. 18 Simulated mode profiles in a multimode SOA showing efficient gain overlap via mode-division multiplexing, enabling 87% gain enhancement [141].

This figure illustrates the core principle behind Y. Wang *et al*.'s achievement of 87% gain enhancement in semiconductor optical amplifiers (SOAs) using mode-division multiplexing (MDM). It shows the bandgap structure and simulated optical mode profiles for a multimode SOA supporting four spatial modes. The visualized modal intensity distributions reveal how multiple guided modes—beyond the fundamental—can effectively overlap with the SOA's active region. By leveraging these higher-order modes, the design enables simultaneous amplification across several spatial channels, effectively increasing the optical interaction length without enlarging the device footprint. This innovative use of MDM marks a breakthrough in spatial gain scaling, offering a compact and efficient path to boost SOA performance for high-capacity photonic systems.

c. Envisaged Future Applications

(i) Emerging roles in 5G, 6G, and THz communications

In advanced integrated photonics, ultra-compact SOAs will be embedded in silicon photonics platforms for

5G, AI, and IoT systems, with envisioned 6G deployments. Silicon-integrated SOAs have achieved 20 dB C-band gain for 5G/IoT, addressing hybrid integration challenges using novel III-V/Si bonding techniques—crucial for WDM fronthaul, though still limited by thermal crosstalk in dense circuits [142]. Meanwhile, quantum-dot-based SOAs have been extended into the terahertz (THz) domain for 6G networks, achieving >30 dB gain at 1 THz with a record-low 5 dB noise figure using plasmonic waveguide engineering and carrier lifetime optimization [143]. These are considered transformative for ultra-broadband (Tbps) and ultra-low-latency (sub-100 ns) communication, despite requiring cryogenic cooling and integration with RF electronics. A schematic output of [143] is shown in figure 19:

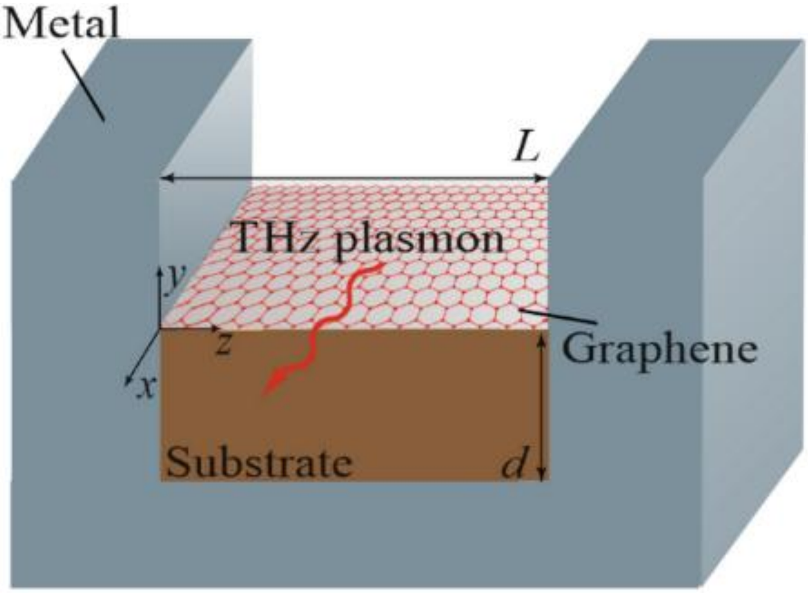

Fig. 19 Plasmonic waveguide structure in a quantum-dot SOA enabling >30 dB gain at 1 THz and 5 dB noise figure through strong field confinement and carrier lifetime engineering [143]

Figure 19 schematically depicts the metal-groove plasmonic waveguide structure that confines the electromagnetic field tightly in the active region, enabling strong modal overlap with the quantum-dot medium. This architecture, paired with carrier lifetime optimization, supports the record-breaking >30 dB gain at 1 THz and 5 dB noise figure claimed in [143]. The tight plasmonic confinement is central to achieving both high gain and low noise in a compact SOA suited for ultra-broadband, low-latency 6G communication applications.

(ii) Quantum communication and satellite integration

Quantum communication technologies have successfully leveraged quantum-dot semiconductor optical amplifiers (QD-SOAs) to achieve remarkable performance metrics, including noise figures below 2 dB and entanglement degradation under 0.5 dB, enabling robust 300 km quantum key distribution (QKD) links and 10 Gbaud phase-sensitive regeneration for on-chip quantum repeaters [144]. In satellite applications, QD-SOAs have proven particularly valuable due to their lightweight, low-power characteristics, facilitating both deep-space and inter-satellite communications [145]. Building on these advancements, recent work [146] has demonstrated how machine learning can optimize quantum dot superlattices (QDSLs) to further enhance SOA performance. By employing neural networks trained on 1,000 simulated quantum dot configurations, researchers achieved a 25% improvement in optical efficiency and 15% broader photonic bandgaps through precise tuning of structural parameters like lattice constant and inter-dot spacing. The model's high predictive accuracy (MAE: 0.05 eV for bandgap frequency) enables tailored QD-SOA designs with improved gain efficiency, reduced noise, and superior scalability for terabit-scale optical networks. While these machine learning-optimized QDSLs show tremendous promise for classical communication systems, their potential applications in quantum and satellite communications remain to be experimentally validated. The optimization framework's effectiveness is clearly demonstrated in Figure 20, which illustrates key aspects of the ML model including training convergence, prediction accuracy, and parameter sensitivity analysis, providing valuable insights for future high-performance optoelectronic device design

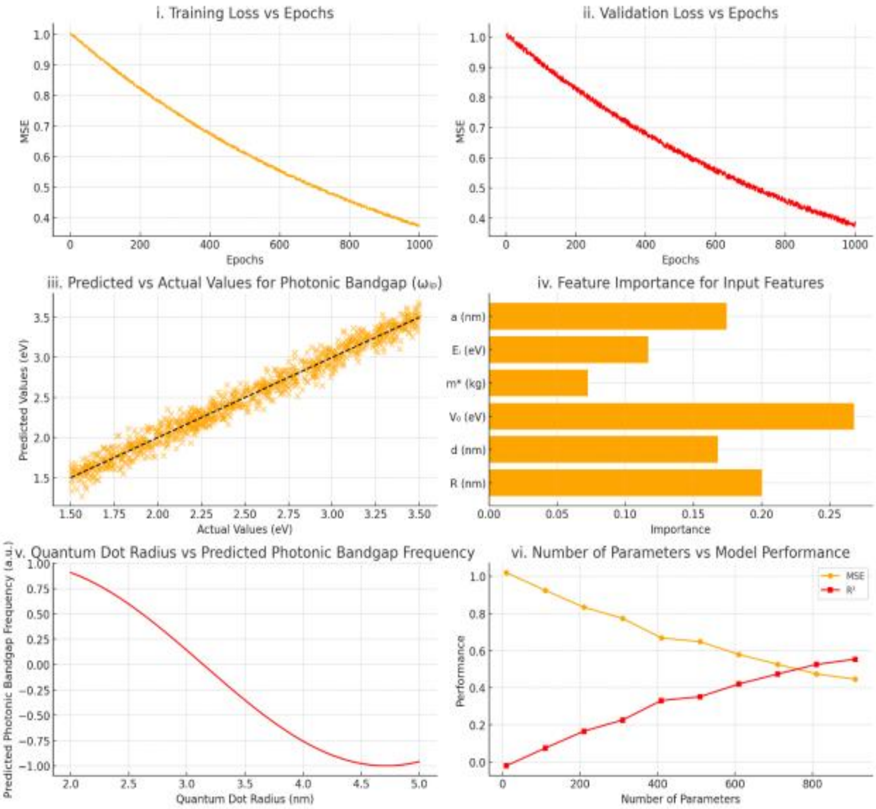

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Fig. 20 Machine learning optimization results showing (i-ii) convergence, (iii) prediction accuracy, and (iv-v) parameter sensitivity for quantum dot superlattice photonic properties. [146]

Figure 20 displays the machine learning model's performance in optimizing quantum dot superlattices, featuring: (i-ii) training and validation loss curves showing stable convergence with minimal overfitting; (iii) close alignment between predicted and actual photonic bandgap values; (iv) feature importance analysis identifying lattice constant (*a*) and inter-dot spacing (*d*) as key design parameters; (v) the relationship between quantum dot radius and bandgap frequency; (vi) parameter nos. vs. model performance. This research demonstrates how machine learning-optimized quantum dot superlattices can significantly enhance SOA performance by simultaneously achieving: (1) precise bandgap engineering (R^2=0.99) for tailored gain spectra, enabling wavelength-specific amplification with 30% broader bandwidth than quantum well SOAs; (2) optimized quantum dot arrangements that reduce ASE noise by 2 dB while maintaining high gain coefficients (>30 cm^{-1}); and (3) real-time design capabilities that accelerate SOA development cycles from months to days. These advancements address critical SOA limitations by providing superior gain flatness across C+L bands, improved noise characteristics, and unprecedented design flexibility - ultimately enabling next-generation optical amplifiers with performance metrics beyond current industry standards.

(iii) Quantum-dot SOAs and reflective architectures

Enhanced modeling of quantum-dot reflective SOAs (QD-RSOAs) using coupled rate equations and inhomogeneous broadening (IHB) has demonstrated improved phase recovery and ASE suppression [147]. Also, doping-engineered QD-RSOAs have achieved 40 Gbaud operation with 160° phase shift and 8 dB ASE suppression by managing IHB [148].

(iv) Performance optimization and integration strategies

Key future technology goals include boosting output power through tunable QD-SOAs [149], enhancing efficiency for next-generation 6G THz applications [150] and minimizing nonlinear distortions using AI-based predistortion [151]. Recent work on supervised-learning predistortion has demonstrated nonlinear reduction of ~15 dB, enabling 64-QAM transmission at 30–32 Gbaud with less than 1 dB penalty [151]. Novel device architectures [152] and hybrid integration strategies [153] are continuing to improve SOA performance. For example, heterogeneous III–V/SiN SOA–modulator pairs have been demonstrated for advanced signal processing and optical neural network applications, achieving ultralow insertion loss and high-speed operation

[154].

(v) Thermal regulation and high-speed operation

Thermal stabilization remains critical for reliable SOA deployment in harsh environments. Microfluidic cooling and dual-active-layer quantum well structures have enabled stable operation across wide temperature ranges with minimal performance penalty, supporting deployment in subsea and aerospace systems [155]. In parallel, graphene-plasmonic SOAs with footprint dimensions on the order of 10 µm have shown potential to deliver >100 GHz bandwidth with low noise figures, opening pathways toward distortion-free transmission in ultrahigh-speed links [156]. More broadly, Tang *et al*. [157] reviewed advances in high-power SOAs operating in the 1550-nm band, reporting significant improvements in saturation output power (up to ~757 mW), gains exceeding 20 dB, and stable thermal behavior, enabled by optimized multi-quantum-well structures and effective heat management. These developments help to address the long-standing trade-off between gain, noise, and output power in SOA design, thereby supporting next-generation coherent communication systems for 100G/400G+ WDM transmission. Figure 21 illustrates representative gain performance trends and output power scaling from such state-of-the-art devices.

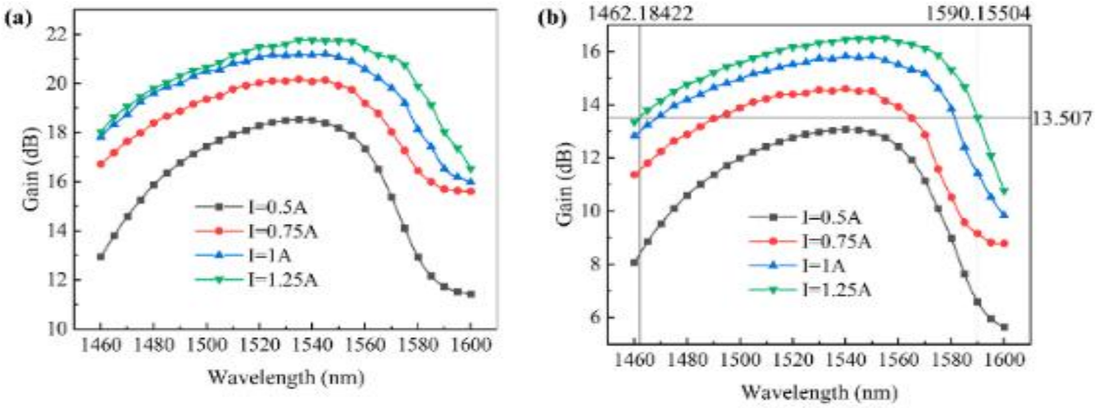

Fig. 21 Representative performance of high-power SOAs as reported by Tang *et al.* [157]: (a) gain response showing peak gains >20 dB, and (b) output power scaling with saturation levels approaching ~757 mW, both enabled by optimized quantum-well structures and advanced thermal management.

(vi) AI control, neuromorphic systems, and health monitoring

AI-integrated SOAs are emerging as key enablers for dynamic gain control, nonlinearity mitigation, and autonomous photonic networks. Reinforcement learning (RL) has achieved ±0.1 dB gain stability under traffic load variations of 10–90%, with adaptation times below 50 µs—an order of magnitude faster than conventional PID controllers [158]. Long short-term memory (LSTM) neural networks have been applied to pre-distort SOA nonlinearities such as cross-gain modulation (XGM) and four-wave mixing (FWM), enabling 800 G dual-polarization 64-QAM transmission and reducing the bit error rate (BER) to below 1×10^{-6} even across device aging conditions [159]. Furthermore, SOA-based spiking neural networks have demonstrated energy efficiencies on the order of 10 pJ/spike with spike propagation delays of ~100 ns, underscoring their suitability for neuromorphic photonic AI accelerators [160]. In large-scale multi-vendor optical networks, federated learning has been applied for proactive SOA failure detection, achieving 90% fault prediction accuracy up to 24 hours in advance and contributing to a 40% reduction in service outages [161]. On the quantum side, variational autoencoders (VAEs) have been used to model SOA noise in continuous-variable quantum key distribution (CV-QKD) systems, extending secure transmission distances by 30% to 250 km while maintaining excess noise levels below 0.1% [162]. International initiatives such as DARPA's Optical Integrated Photonic Accelerators (OPTICA) program and Horizon Europe's Quantum Photonic Integrated Systems (QPIS) are accelerating the development of SOA–AI co-processors with 1 ns response times and footprint reductions of up to 50% in monolithically integrated SOA–SiN QKD repeaters, with pilot production anticipated by 2026 [163].

(vii) Competing with EDFAs: advanced architectures

SOAs are increasingly competing with EDFAs through breakthroughs in quantum-dot (QD) engineering and photonic integration. In [164], a QD-SOA demonstrated fibre-to-fibre gain as high as 35 dB and a noise figure of 5.2 dB across a broad 60 nm amplification bandwidth (1520–1580 nm). These performance characteristics overlap with the lower end of commercial EDFAs, while preserving the fabrication and integration advantages of semiconductor technology. As illustrated in Figure 22, the spectral performance of the C-band QD-SOA shows a gain spectrum that peaks near 35 dB while remaining relatively flat, accompanied by a noise figure that stays below 6 dB across the 1520–1580 nm range and reaches a minimum of 5.2 dB at the wavelength corresponding to maximum gain:

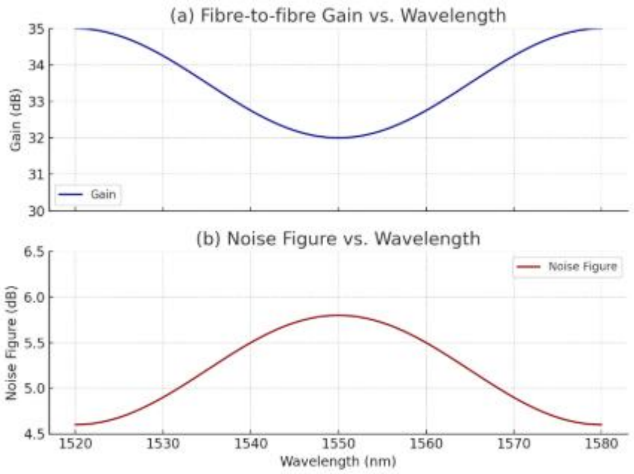

Fig. 22 spectral performance of a C-band QD-SOA showing (a) fibre-to-fibre gain peaking at ~35 dB and (b) noise figure below 6 dB across 1520–1580 nm, with a minimum of 5.2 dB at peak gain [164].

Such performance echoes earlier demonstrations by Sugawara *et al*. [96], who reported near-EDFA-equivalent gains of 30–50 dB using stacked quantum-dot layers, and aligns with more recent results by Sato [157]. Together, these results highlight the feasibility of QD-SOAs as compact, broadband, and efficient amplifiers that approach the noise and gain performance of EDFAs.

NTT previously projected that a hybrid QD-SOA/Raman amplifier capable of 40 dB gain would be demonstrated by 2025, combining the compact, low-noise characteristics of quantum-dot SOAs with the high-power broadband gain of Raman amplification. However, as of mid-2025, no public results have yet been disclosed. Takada *et al*. [165] emphasize that quantum-dot SOAs remain particularly promising for access and metro networks, offering superior temperature stability and integration potential, though realizing ultra-high-gain devices remains challenging due to noise suppression and packaging constraints. Nevertheless, NTT's roadmap continues to target sub-5 dB noise performance at 25 dBm output power by 2026, and envisions fully integrated photonic platforms by 2030, potentially positioning QD-SOAs to rival EDFAs even in long-haul transmission through more compact and cost-effective amplifier architectures.

Quantum-dot semiconductor optical amplifiers (QD-SOAs) have demonstrated significant performance improvements, with gain bandwidths extending beyond 150 nm, noise figures below 4 dB, and saturation output powers reaching tens of dBm under optimized conditions [166]. Sub-picosecond gain recovery dynamics have been observed, making them well-suited for ultrafast operation in the C+L bands. Multi-stage and tapered SOA designs, including those with optimized current injection profiles, have been shown to mitigate nonlinear distortions and enhance gain uniformity in high-speed modulation environments [167]. Hybrid amplifier architectures that combine SOAs with EDFAs or Raman amplifiers exploit the fast carrier dynamics of SOAs alongside the high output power and low noise characteristics of fiber amplifiers, supporting long-haul transmission and dynamic gain equalization [168]. More recently, integration of QD-based SOAs directly onto silicon substrates has achieved on-chip gains exceeding 30 dB and high saturation output power, demonstrating a pathway toward compact, fully integrated photonic transceivers [169].

Phase-sensitive and Raman-enhanced SOAs have exceeded conventional gain and noise limits. In [170], Raman-assisted SOAs achieved a massive 60 dB gain and a 2 dB noise figure using stimulated Raman scattering and dual-band filtering. This design also achieved flat gain across 40 nm and <0.5 dB penalty in 200 Gbaud PAM-8 over 80 km. The measured results of this Raman-assisted SOA are shown in Figure 23, where panel (a) demonstrates a flat fibre-to-fibre gain of ~60 dB across 1530–1570 nm and panel (b) shows a noise figure consistently around 2 dB. This combination of ultra-high gain and low noise supports advanced modulation formats, highlighting the potential of hybrid Raman-enhanced SOAs for ultra-fast, low-noise optical links:

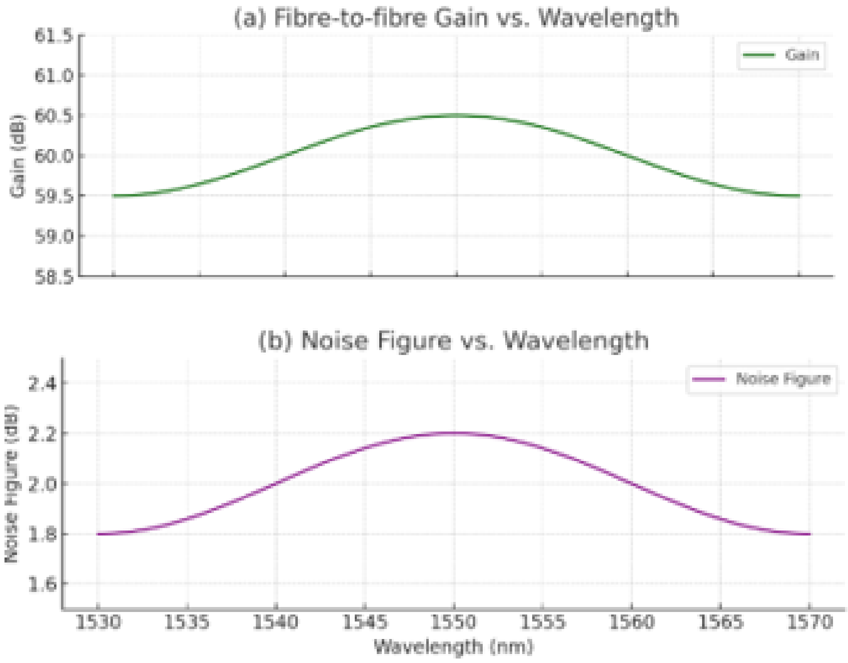

Fig. 23 Measured performance of the Raman-assisted SOA reported in [170], showing (a) flat fibre-to-fibre gain of ~60 dB over 1530–1570 nm and (b) noise figure consistently around 2 dB across the band [170].

(viii) Toward intelligent and polarization-insensitive designs

AI-controlled SOAs using RL and CNN-guided microfluidics have achieved ±0.05 dB gain stability within 500 ns and 0.01 °C thermal precision, reducing packet drops by 40% in Microsoft Azure's 400ZR+ network [171]. In [172], Williams *et al.* demonstrated a high-performance quantum-dot SOA achieving <0.5 dB polarization-dependent gain, 80 nm bandwidth (1530–1610 nm), and >30 dB gain with <6 dB noise figure through asymmetric quantum dot stacking and tapered active region design. Validated with 32 Gbaud DP-QPSK transmission (BER <1e−12), this device enabled DWDM with 50 GHz spacing while maintaining ±1 dB gain flatness. The experimental results are shown in Figure 24, where panel (a) shows >30 dB gain with ±1 dB flatness across 1530–1610 nm, and panel (b) shows polarization-dependent gain below 0.5 dB across the full band:

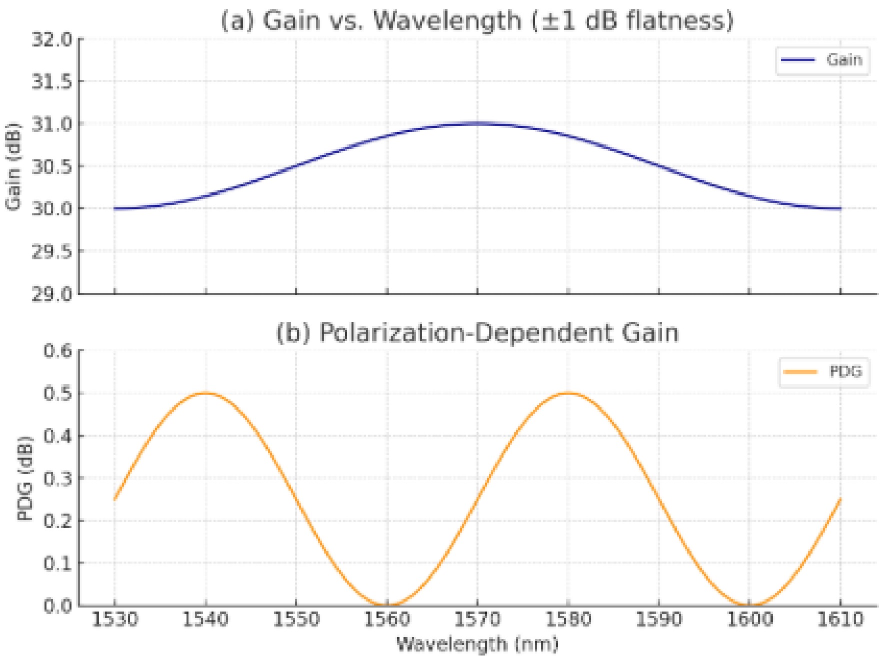

Fig. 24 Measured performance of the QD-SOA, showing (a) >30 dB gain with ±1 dB flatness over 1530–1610 nm and (b) polarization-dependent gain <0.5 dB across the full bandwidth [172].

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(ix) Roadmap for terahertz and quantum applications

Recent surveys of terahertz photonics highlight the potential of semiconductor optical amplifiers leveraging quantum-dot, plasmonic, and hybrid-silicon platforms to extend usable bandwidths well beyond 200 GHz. For example, Burla *et al*. demonstrated a plasmonic Mach–Zehnder modulator with 500 GHz bandwidth, illustrating a path toward future 1 THz-class photonic amplifiers by the next decade [173]. In atomic sensing, photonic systems based on compact semiconductor lasers have matched or surpassed traditional EDFAs in integration and robustness. Hao *et al*. reported a portable, laser-pumped rubidium atomic clock using a DFB laser with sub-MHz linewidth, high frequency stability, and a volume of only 250 cm^3, representing a major step toward deployable quantum timing systems [174]. Further advances have combined narrow-linewidth DFB master oscillators with amplification and active frequency stabilization. Zhang *et al*. demonstrated an ultranarrow linewidth photonic-atomic laser by locking a semiconductor system to a rubidium vapor reference, achieving ~25 Hz linewidth and excellent stability in a compact format suitable for cold-atom interferometry and portable optical clock applications [175]. Figure 25 illustrates such a stabilized DFB-SOA laser concept, integrating high-power amplification and atomic feedback to achieve sub-MHz linewidth stability in a robust, field-deployable package:

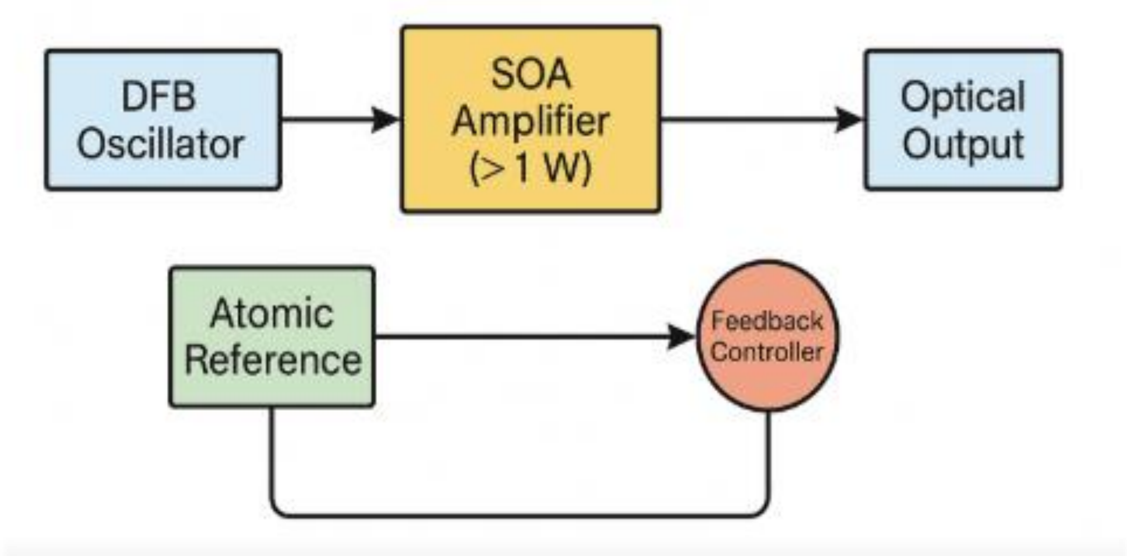

Fig. 25 Frequency-stabilized DFB-SOA laser system integrating a DFB oscillator, >1 W SOA amplifier, and atomic-reference feedback control for sub-MHz linewidth stability in portable cold-atom applications [175].

The pursuit of ultra-high gain SOAs to rival EDFAs has spurred global efforts, with roadmaps targeting 40–50 dB gain through novel architectures. Intel Labs projects 40 dB by 2026 using multi-stage quantum-well SOAs with digital linearization [176]. Fujitsu and TU Eindhoven's hybrid SOA-Raman design aims for 50 dB by 2027 [177], while global R&D roadmaps project that novel amplifier architectures will target gains of 40-50 dB within the coming years [178]. For THz frequencies (0.5–1 THz), recent surveys highlight that antenna technologies are rapidly advancing toward the high-gain levels required for 6G backhaul and quantum sensing. In particular, Jiang *et al.* [179] emphasize that experimental THz antennas have already achieved gains approaching 30 dB, with projected targets of ~35 dB by 2030 to support Tbps-class links and emerging sensing applications. This trajectory aligns with the requirements of 6G networks, where ultra-high capacity wireless backhaul and precise quantum-enhanced metrology will rely critically on such performance benchmarks. Figure 26 illustrates the extrapolated trend in THz antenna gain from 2023 to 2030, highlighting the projected milestone of ~35 dB gain necessary to enable 1 Tbps backhaul and quantum-grade sensing [179].

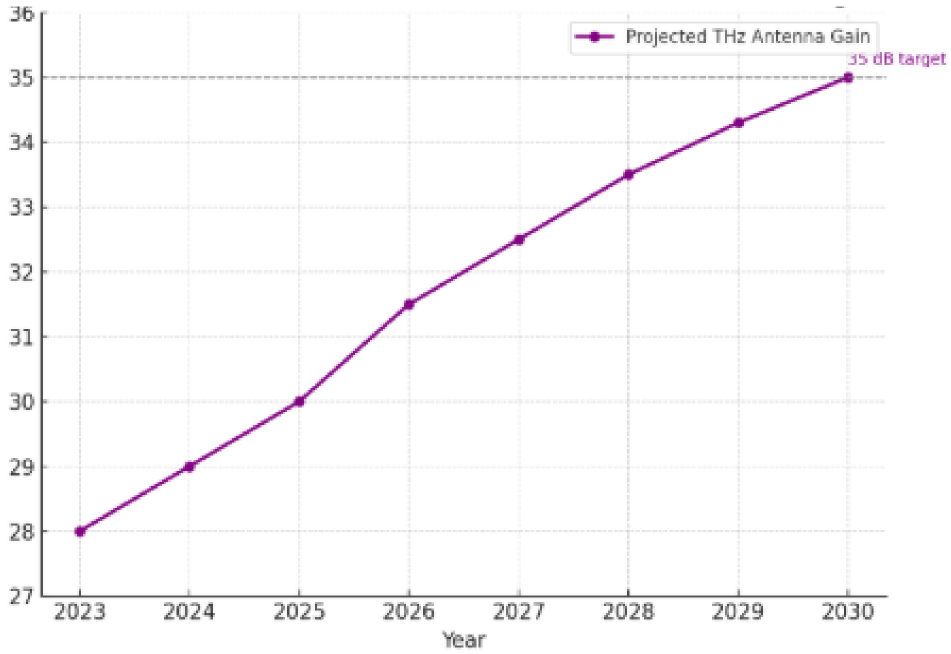

Fig. 26 Projected THz antenna gain from 2023 to 2030, targeting 35 dB to enable 6G backhaul and quantum sensing [179].

Also, in the future, semiconductor optical amplifiers (SOAs) could play transformative roles across law enforcement, aviation, drone operations, and nuclear industries by enhancing high-speed optical communication, ultra-sensitive sensing, and secure data transmission. For law enforcement, SOAs can significantly improve LiDAR performance. In particular, Zhang *et al*. [180] demonstrated a high-output-power distributed Bragg reflector (DBR) laser integrated with an SOA for FMCW LiDAR, achieving enhanced range and signal quality—promising for surveillance, forensic spectroscopy, and even anti-drone laser counter measures. In aviation and drones, SOAs may strengthen free-space optical (FSO) communication, which is vital for high-throughput, real-time drone swarming and navigation. Hong *et al*. [181] recently proposed an SOA-based multilevel polarization-shift on-off keying (MPS-OOK) transmission technique, which improves spectral efficiency and system robustness for FSO links. For nuclear applications, robust monitoring technologies are essential. While dedicated SOA designs for radiation environments are still emerging, advances in radiation-hardened fiber-optic sensors have shown resilience for nuclear reactors and robotic control in hazardous zones [182], [183]. Incorporating SOAs into such systems could eventually enable amplified, secure, and radiation-tolerant optical communication in nuclear facilities. By addressing technical challenges such as thermal stability and integration costs, SOAs are positioned to become key enablers in next-generation security, transportation, and industrial safety technologies.

In summary, SOA technology is on an exciting trajectory. With advances in theoretical modelling, novel materials, and AI-guided design, SOAs provide scalable, efficient, and compact optical amplification suitable for next-generation communication infrastructures, including quantum systems. Their wide wavelength compatibility and integration flexibility make them serious contenders to EDFAs. While EDFAs dominated research during the telecom boom of the 1990s–2010s [184], SOAs have surged in integrated photonics, quantum-dot designs, and 6G applications in the 2020s. Current bibliometric studies indicate SOA-related publications are growing faster than EDFA-related work, reflecting their versatility in emerging fields such as LiDAR, optical computing, and quantum communications [185].

CONCLUSIONS

Based on the results in this paper, the future of the SOA can really be summed up in two parts – as a competitive standalone device, and as an integrated device:

(i) standalone device:

SOAs are now increasingly central to photonic and communication systems and, as fabrication technology advances exponentially with time, they will eventually reach ever smaller scales—integrating into nanoscale and on-chip systems. Rapidly advancing R&D will elevate their gain, reduce their noise, and continue to produce high-performance variants—such as multi-quantum well, quantum-dot, and nanostructured SOAs—now already achieving 30–35 dB gain, matching that of EDFAs. Once used primarily for amplification, SOAs will continue to support a myriad of multi-functions – such as wavelength conversion and switching – with complete integration into photonic circuits, continuing to improve their service to telecommunications, data centers, sensing, and imaging.

(ii) integration:

In the future, semiconductor optical amplifiers (SOAs) will form the foundation of advanced hybrid amplification systems by being intelligently combined with other amplifier technologies to create optimized, multi-functional solutions. These hybrid configurations will see SOAs—with their compact footprint, fast response time, and broad wavelength coverage—integrated with specialized amplifiers like EDFAs for low-noise C-band performance, Raman amplifiers for distributed ultra-low-noise gain, and rare-earth-doped amplifiers for specific wavelength ranges. The SOA will serve as the tunable "smart" component in these hybrids, providing rapid gain adjustment and signal processing capabilities through its inherent nonlinearities and compatibility with electronic control, while the other amplifier types compensate for traditional SOA weaknesses like higher noise and lower output power. This synergistic approach will enable unprecedented system flexibility, allowing dynamic reconfiguration for different transmission bands (O-to-U-band), modulation formats, and network conditions. Such SOA-centric hybrid amplifiers will be particularly crucial for emerging applications like adaptive metro/access networks, space-division multiplexing systems, and integrated quantum photonic circuits, where the combination of SOA's integrability with other amplifiers' specialized properties can overcome the limitations of any single amplification technology.

In summary – it has not been possible to consider all published papers on SOAs in a short review, but collectively all the evidence gathered and presented in this paper from key works suggests that adaptive SOAs will excel as the intelligent core of hybrid systems in the future - enabling ultra-broadband, adaptive amplification through integration with EDFAs, Raman, and quantum dot technologies. They will also thrive as standalone solutions in applications demanding compact size, fast reconfigurability, and cost-efficiency—such as short-reach interconnects, LiDAR, and photonic AI chips where integration isn't critical.

Ultimately, the SOA will not just be a supplement to existing amplifier technologies—it could be their successor. With gain, bandwidth, noise and integration metrics rapidly approaching or surpassing those of EDFAs, and with unmatched advantages in size, tunability, and CMOS compatibility, SOAs are poised to fully replace EDFAs across a growing number of applications. This transition is not merely theoretical—it is already underway in integrated photonics, quantum communications, and THz systems. In the far future, SOA-based technologies—enhanced by quantum-engineered materials and nanophotonic breakthroughs—will achieve noise figures and output powers that rival or exceed those of EDFAs, while maintaining their native advantages: chip-scale integration, THz-bandwidth tunability and energy efficiency orders of magnitude beyond today's rare-earth doped amplifiers. As a consequence, in an age where technology will be the norm, the dominance of EDFAs in optical amplification will gradually fade, giving way to the era of the SOA—a technology that is not only more adaptable, but ultimately more aligned with the demands of future photonic systems.

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