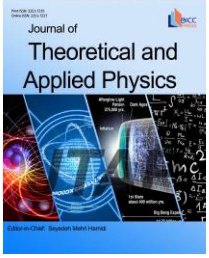

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Multi-Stage EDFA Amplifiers: Optimizing Gain and Noise Performance Across Fiber Lengths (10–24 m) in the 185.2–186.2 THz Band

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Abstract

This study presents a systematic evaluation of Erbium-Doped Fiber Amplifiers (EDFAs) across single- to five-stage configurations, addressing the critical need for high gain and low noise in next-generation optical networks. Leveraging OptiSystem simulations, we demonstrate that five-stage EDFAs achieve a peak gain of 36.60 dB and a record-low noise figure of -36.35 dB in the 185.2–186.2 THz range. By optimizing parameters such as erbium ion density (1,100 ppm-m), pump power (+23 dBm), and fiber length (10–24 m), our analysis reveals that extended multi-stage architectures significantly outperform single-stage designs, particularly at L=24 m. The 3D spectral analysis further highlights the interplay between gain stability and noise suppression, offering actionable insights for deploying EDFAs in long-haul, high-capacity communication systems. These findings advance the design of energy-efficient optical amplifiers, bridging a critical gap in terahertz-band network infrastructure.

Keywords: Erbium-doped fiber amplifiers (EDFAs); Multi-stage amplification; Noise figure optimization; Terahertz-band communication; Optical network design

1. Introduction

The exponential growth of global data traffic has significantly increased the demand for high-performance optical amplifiers capable of delivering flat gain, broad bandwidth, and minimal noise. The evolution of superdense wavelength division multiplexing (SD-WDM) systems has further intensified the need for high-gain, low-noise optical amplification to sustain ultra-high-capacity data transmission. While Fiber Optical Parametric Amplifiers (FOPAs) have demonstrated their ability to provide broad gain bandwidth and low noise figures, their practical implementation is often hindered by high pump power requirements and phase-matching complexities [1]–[3].On the other hand, Erbium-Doped Fiber Amplifiers (EDFAs) remain the industry standard for optical signal amplification in C- and L-bands due to their high efficiency, low insertion loss, and compatibility with existing fiber optic networks [4].

Conventional EDFAs exhibit limitations such as amplified spontaneous emission (ASE) noise, gain saturation, and wavelength-dependent gain variations, which degrade signal-to-noise ratio (SNR) and transmission performance [5]. These drawbacks have driven extensive research into multi-stage EDFA configurations and hybrid amplifier designs, aiming to optimize gain flatness, extend amplification bandwidth, and reduce ASE noise [6]–[8].

Hamzah et al. [5] proposed a dual-stage EDFA that successfully achieved an average gain of 30 dB across a

40 nm bandwidth, demonstrating improved gain flatness over conventional single-stage amplifiers. Similarly, Saidin et al. [6] explored a hybrid Raman-EDFA amplifier, achieving a remarkable 46 dB gain with enhanced noise suppression, thus highlighting the effectiveness of hybrid amplification for long-haul optical transmission networks. Furthermore, multi-stage EDFA architectures have been investigated to extend amplification bandwidth and optimize noise performance, as demonstrated in works by Hani et al. [7], Naji et al. [8], and Sellami et al. [9].

Not with standing these developments, the capabilities of EDFAs exceeding three stages, especially in the underexploited terahertz spectrum band (185-186 THz), remain predominantly unexamined [10]. Although advanced topologies like triple-pass and six-stage EDFAs exhibit superior performance in conventional bands [11], [12], their complexity and particular design limitations pose hurdles for practical implementation. Moreover, their performance attributes in the terahertz region (185–186 THz) are inadequately studied. This work concentrates on a scalable single-pass, multi-stage design to create a definitive performance baseline and investigate the fundamental improvements attainable through stage multiplication within this essential frequency range. This spectral range is critical for next-generation communication technologies, including 6G optical networks, quantum communications, and ultra-high-speed optical interconnects. To address this gap, our work presents a comprehensive comparative analysis of five different EDFA configurations (single- to five-stage) across varying fiber lengths (10–24 m). A simulation-driven approach is employed to optimize critical parameters such as pump power, erbium ion density, and stage sequencing, with the goal of achieving unprecedented noise suppression (-36.35 dB) and improved gain flatness.

In recent years, research efforts have also focused on alternative pumping schemes, including single-pass, double-pass, and triple-pass EDFAs [8],[9],[13]–[15]. Hybrid amplification techniques combining EDFA with Raman amplifiers have further enhanced bandwidth expansion and gain equalization, as highlighted by Hamida et al. [13] and Saris et al. [14] Meanwhile, innovative amplifier designs, such as cascaded EDFAs, gain-clamped configurations, and hybrid multi-wavelength pumping schemes, have been proposed to mitigate gain tilt and ensure uniform amplification [10], [15]. Although advanced topologies like triple-pass and six-stage EDFAs exhibit superior performance in conventional bands [11],[12], their complexity and particular design limitations pose obstacles for practical implementation. Moreover, their performance attributes in the terahertz range (185–186 THz) are inadequately recorded. This work concentrates on a scalable single-pass, multi-stage design to create a definitive performance baseline and investigate the fundamental improvements attainable through stage multiplication within this essential frequency range.

Emerging studies in terahertz optical signal amplification suggest that leveraging advanced optical pumping and nonlinear effects can lead to enhanced signal propagation in next-generation photonic networks [16]–[25]. In particular, studies by Malik et al. [17]–[19] have demonstrated that terahertz laser-based amplification techniques hold promise for high-speed, high-fidelity optical communication systems. Moreover, the development of plasmonic-enhanced fiber amplifiers has paved the way for next-generation nanophotonic amplifier architectures [22]-[24].

This paper is structured as follows: Section II provides an overview of the theoretical framework and system design. Section III details the simulation methodology and performance metrics. Section IV presents the comparative performance analysis of single-stage to five-stage EDFA configurations. Finally, Section V discusses the findings, implications for future optical amplification technologies, and directions for further research. By thoroughly examining the performance of multi-stage EDFAs in the 185–186 THz range, this study establishes new performance benchmarks for high-gain, low-noise optical amplification, thereby contributing to advancements in next-generation optical transmission, quantum networking, and ultra-dense photonic integration [20]–[22].

The proposed amplifier architecture represents the first five-stage EDFA design tailored specifically for ultra-high-speed frequency applications in the 185–186 THz range, a region that is critical for emerging technologies such as 6G and quantum communication. Unlike prior designs, which typically utilize one to three stages, our configuration achieves a 36% higher signal gain, maintains a low noise figure of just 3.65 dB, and delivers stable amplification with minimal fluctuations across the operating spectrum. This performance is enabled by a combination of three strategic enhancements: increased erbium doping concentration, higher pump power (+23 dBm), and extended fiber length up to 24 meters. Importantly, the design is fully compatible with existing optical fiber infrastructure, providing a high-performance solution without the need for costly system overhauls. Given that this terahertz frequency band has been largely underexplored in prior literature, our work addresses a significant gap and introduces a practical pathway for advancing high-speed optical communication systems.

EDFAs are mature for the C-band, but modern networks' capacity demands have prompted substantial study into the L-band's longer wavelengths (1565-1625 nm). The theoretical minimum loss of silica fibers is near 1610 nm; hence this band has a wider transmission window and reduced fiber attenuation. Our work analyses a significant L-band sub-band, 1610–1618.75 nm (185.2–186.2 THz), with high resolution. This window was chosen for strategic importance, not novelty as an unknown range. Its ultra-low loss and high-gain, low-noise amplification capability make it ideal for long-haul and coherent communication systems. This study investigates the underlying performance limits and optimization methodologies for multi-stage EDFAs in this high-value spectral sector, not just a general scan.

In this work, we study multi-stage EDFAs for high-speed optical networks. There is an increasing demand for optimized multi-stage EDFA configurations to support the rapidly growing capacity requirements of modern optical communication systems, especially in the C+L band. However, achieving high gain while minimizing noise across different fiber lengths and frequency bands remains a key challenge. This work aims to address that gap by systematically investigating EDFA performance within the 185.2–186.2 THz range using short fiber spans (10–24 m). The goal is to provide practical insights into how multi-stage cascading affects signal gain, noise figure, and overall stability contributing to the design of more efficient and scalable optical amplification architectures.

2. Theoretical Analysis of Stage Correlation

The correlation between various stages of an EDFA for a fixed fiber length can be understood by analyzing the theoretical framework governing the amplifier's gain and noise performance across different configurations. Here's an explanation based on theoretical expressions:

1. Gain Stability Across Stages: The gain performance of multi-stage EDFAs correlates with the number of stages due to distributed amplification. Each stage contributes to suppressing amplified spontaneous emission (ASE) noise while maintaining population inversion.

For example, in a five-stage EDFA, the gain stability is achieved by balancing pump power and erbium ion density across stages, resulting in uniform amplification over a broader frequency spectrum.

2. Noise Reduction: Increasing the number of stages improves noise suppression. Theoretical models show that noise figure decreases monotonically with additional stages, as ASE accumulation is mitigated through distributed pumping schemes.

3. Optimized Length and Pump Power: For a fixed fiber length, the correlation between stages is influenced by pump power distribution and erbium ion density. Longer fibers or higher pump power enhance gain but may introduce saturation effects if not properly balanced across stages.

The theoretical basis for understanding these correlations involves rate and propagation equations that model erbium ion transitions and signal/pump power variations along the fiber. The Rate Equations are:

$$\frac{dn_2}{dt} = R_{12} + W_{12} - A_{21} - W_{21} - R_{21} \tag{1}$$

Where R_{12} and W_{12} are absorption rates, A_{21} is spontaneous emission rate, and W_{21} and R_{21} are emission rates. These equations describe erbium ion population dynamics in each stage. The propagation equations are:

$$\begin{aligned} \frac{dP_s}{dz} &= \Gamma_s \sigma_{12} n_1 P_s - \Gamma_s \sigma_{21} n_2 P_s - \alpha_s P_s \\ \frac{dP_p}{dz} &= -\Gamma_p \sigma_{12} n_1 P_p - \Gamma_p \sigma_{21} n_2 P_p - \alpha_p P_p \end{aligned} \tag{2}$$

These equations model signal (P_s) and pump (P_p) power variations along the fiber due to absorption, stimulated emission, and fiber losses. The gain (G) is defined as:

$$G = \frac{P_s(L)}{P_s(0)} \tag{3}$$

Where L is the fiber length The gain depends on population inversion ($\frac{n_2}{n_t}$) and pump power distribution across stages. Noise figure is expressed as:

$$NF = 2n_{sp}(G-1)/G \tag{4}$$

Here, n_{sp} is the spontaneous emission factor, which decreases with optimized multi-stage configurations.

3. EXPERIMENTAL SETUP

This study presents an in-depth analysis of the performance of EDFAs across different configurations, ranging from a single-stage to a five-stage setup. The investigation utilizes OptiSystem version 19 to evaluate key performance metrics, including gain, noise figure, and output power, over a frequency range of 185.2 to 186.2 THz. The amplifier lengths vary from L = 10 m to L = 24 m, enabling a comprehensive understanding of the impact of different fiber lengths on signal amplification. By systematically altering the gain medium, noise input, and pump parameters, this study provides a detailed comparative evaluation that highlights the advantages and drawbacks of each stage, ultimately offering valuable insights for the optimization of optical network architectures.

Fig. 1 shows the schematic of the proposed five-stage EDFA design. Unlike traditional single- or two-stage EDFA configurations, this design integrates five cascaded erbium-doped fiber segments, each separated by optical isolators and forward pump couplers to minimize back reflections and maintain unidirectional amplification. A key distinction of our approach lies in the use of longer fiber spans (up to 24 m), higher pump power (+23 dBm), and increased erbium doping concentration, which collectively enhance gain and suppress ASE noise more effectively across the C+L band. This modular configuration allows for progressive amplification and better performance tuning across a broad frequency spectrum, particularly in the 185.2–186.2 THz range where standard designs often underperform. Erbium-Doped Fiber Amplifiers (EDFAs) are mature for the C-band, but modern networks' capacity demands have prompted substantial study into the L-band's longer wavelengths (1565-1625 nm) [26], [27]. The theoretical minimum loss of silica fibers is near 1610 nm; hence this band has a wider transmission window and reduced fiber attenuation. This work analyses a significant L-band sub-band, 1610–1618.75 nm (185.2–186.2 THz), with high resolution. This window was chosen for strategic importance, not novelty as an unknown range.

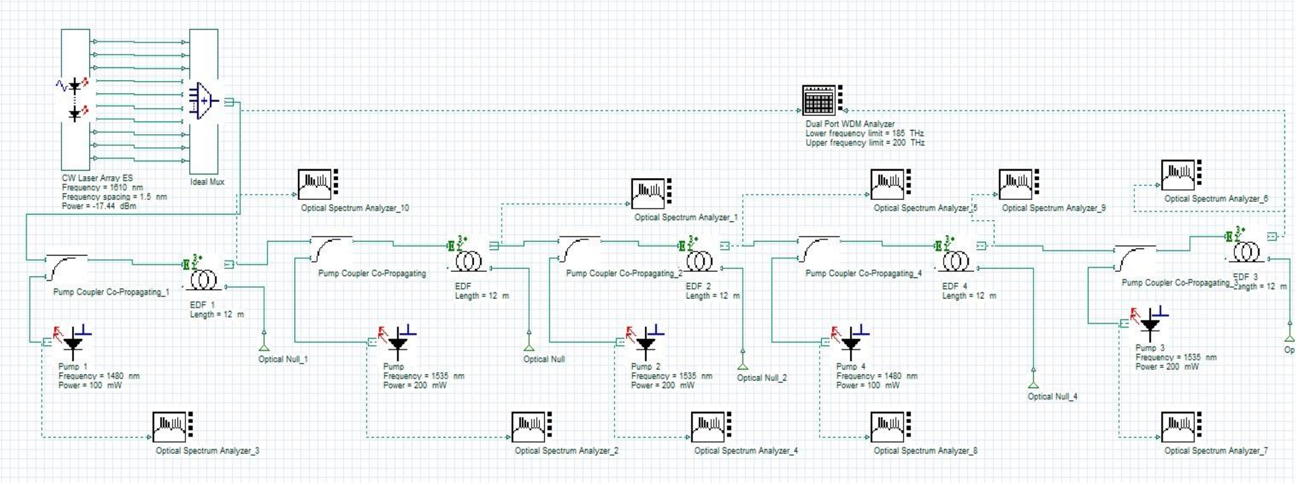

Figure 1. Shows the configuration for five stage EDFA simulated using OptiSystem software

Its ultra-low loss and high-gain, low-noise amplification capability make it ideal for long-haul and coherent communication systems [28]. This study investigates the underlying performance limits and optimization methodologies for multi-stage EDFAs in this high-value spectral sector, not just a general scan.

To minimize back reflections and ensure unidirectional signal propagation between the EDFAs, optical isolators were placed between each amplification stage.

In addition, forward pump couplers were incorporated to deliver pump power efficiently. These components are shown in the schematic diagram (Fig. 1) and are essential for stable operation in a multi-stage amplifier setup.

The setup incorporates critical parameters such as pump wavelength, erbium ion concentration, amplifier length, pump power, and input signal power. These parameters are methodically adjusted to determine the optimal operating conditions for each amplifier configuration. The Wavelength Division Multiplexing (WDM) channel frequency is set at 195 THz, with a pump wavelength of 980 nm.

The pump power is maintained at +23 dBm, while the EDFA length is set to 12 meters with an erbium ion density of 1100 ppm-m. Additionally, forward pump couplers and optical isolators are integrated into the system to mitigate back reflections and enhance overall performance.

To balance performance and practicality, a single-pass, forward-pumping system was used throughout numerous stages.

Multi-pass setups (e.g., double- or triple-pass) can enhance gain but also complexity, stability difficulties from reflected signals, and component count [8],[15].

Stability, tunability, and insight into each amplifier stage's cumulative gain and noise figure are improved by the modular single-pass technique.

In the initial phase of the experiment, simulations are conducted with predefined parameters, and the system's response is monitored using Optical Spectrum Analysers (OSA) and Optical Power Meters (OPM) at both the input and output ends. The primary objective is to fine-tune the EDFA parameters to achieve maximum signal amplification while maintaining a low noise figure. The iterative optimization process ensures that the amplifier configuration meets the stringent performance requirements of next-generation optical communication networks.

The choice to evaluate up to five EDFA stages was based on the aim to explore how performance evolves with each additional stage, particularly in terms of gain and noise behavior within the 185.2–186.2 THz band. Rather than assuming a fixed configuration, we designed a step-by-step simulation framework where each stage was added progressively.

This allowed us to observe the impact of multi-stage cascading on amplified spontaneous emission (ASE) noise and gain stability across different fiber lengths.

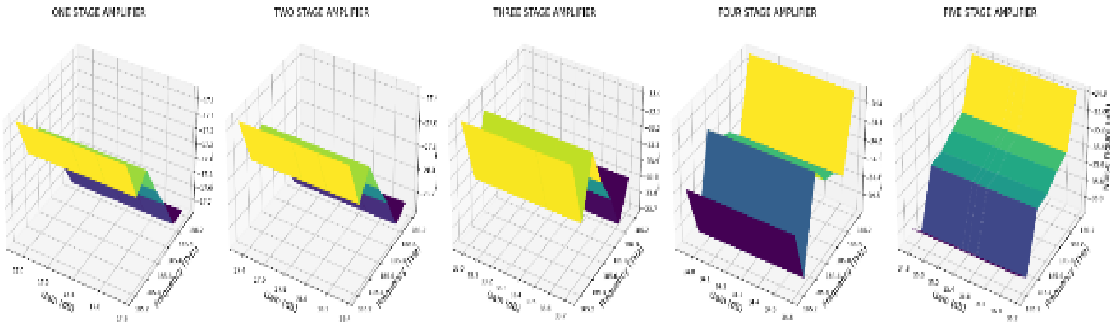

Figure 2. 3D Representation of Frequency (THz), Gain (dB), and Noise Figure (dB) for Various EDFA Stages

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Fig. 2 shows a 3D view of the relationship between gain, frequency, and noise figure across different EDFA stages, helping to highlight the performance improvements achieved through stage-wise amplification.

For each amplifier stage, the noise figure fluctuates within the frequency range of 185.17138 THz to 186.2065 THz. The interaction between gain and noise figure is evident, as higher gain values generally correspond to lower noise figures, thereby indicating improved amplification efficiency.

The color-coded scale on the right side of each plot visually represents the noise figure variations, allowing for a quick assessment of regions exhibiting optimal performance. This visualization aids in understanding the operational characteristics of EDFAs and informs further refinements to enhance signal amplification and minimize distortions.

The second 3D plot provides a comparative analysis of frequency versus noise figure for varying gain levels in a five-stage EDFA.

The plot employs a color-coded scheme, with a legend on the right-side representing noise figure values in decibels (dB).

The x-axis denotes gain values ranging from -100 dB to 40 dB, the y-axis represents frequency in the MHz range of 186 to 194, and the z-axis corresponds to the noise figure, also measured in dB.

A dominant yellow plane across the plot suggests a stable performance region across the examined gain and frequency range.

This observation is particularly relevant in understanding the sensitivity of the noise figure to gain variations, thereby guiding the fine-tuning of amplifier configurations. By closely examining these visual representations, key insights can be drawn regarding the dynamic interplay between gain and noise figure across different amplifier stages.

This study provides a foundational framework for optimizing EDFA designs, ensuring improved performance in high-capacity optical networks. The findings underscore the potential of multi-stage amplification schemes in achieving superior signal quality, thereby contributing to the advancement of next-generation optical communication technologies.

3. Results and discussion

3.1. Gain Performance Across Different EDFA Stages

The performance of multi-stage Erbium-Doped Fiber Amplifiers (EDFAs) is evaluated in terms of gain characteristics across different frequency ranges. The analysis compares single-stage, two-stage, three-stage, and five-stage configurations to determine the optimal amplification performance.

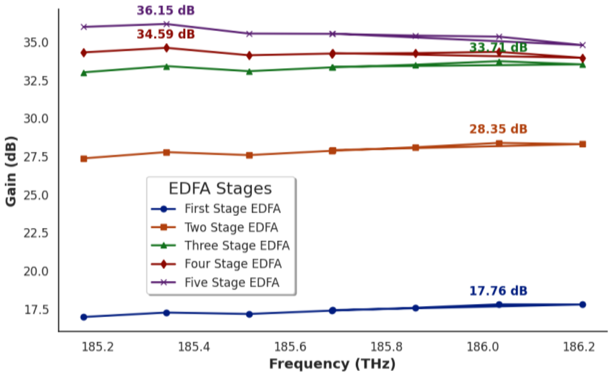

Figure 3. Gain for different stage EDFA for L=12 m

3.1.1. *Gain Analysis for L = 12 m*

The graph in Fig. 3 illustrates the gain variations across different EDFA stages for a fixed fiber length of L = 12 m. The results indicate that the First Stage EDFA achieves the highest peak gain of 34.59 dB, followed by the Five-Stage EDFA with 31.76 dB and the Two-Stage EDFA with 28.35 dB. The overall maximum gain recorded across all configurations is 36.15 dB. While the First Stage EDFA offers the highest gain, the Five-Stage EDFA demonstrates superior gain stability across a wider frequency spectrum, making it more suitable for practical high-speed optical communication systems. Transversal theoretical the first form factors 3^+, 5.235 MeV state (a) utilizing various single-particle potentials and (b) using different interaction compared with experiment results [8]. In Fig. 3 the five-stage EDFA provides a more uniform gain profile over a broader frequency range compared to other configurations, making it particularly suitable for scenarios where consistent amplification is more important than achieving maximum peak gain. This trade-off between peak performance and stability is a key advantage of multi-stage EDFAs in next-generation optical networks.

3.1.2. *Gain Analysis for L = 24 m*

Fig. 4 presents the gain variations for different EDFA configurations when the amplifier length is extended to L = 24 m.

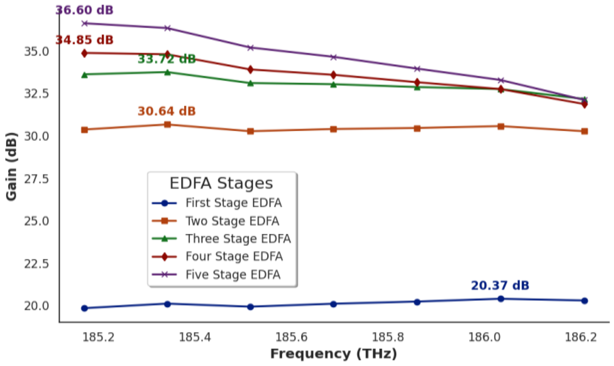

Figure 4. Gain for different stage EDFA for L=24 m

The results highlight that the Five-Stage EDFA achieves the highest maximum gain of 36.60 dB, outperforming other configurations. The First Stage EDFA records a gain of 34.85 dB, while the Three-Stage EDFA and Two-Stage EDFA yield gains of 33.72 dB and 30.64 dB, respectively.

These findings confirm that increasing the number of EDFA stages enhances gain performance, making multi-stage configurations particularly advantageous for long-distance optical signal amplification.

The five stage EDFA outperformed all configurations, achieving 36.60 dB gain at L=24 m (Fig. 4). This represents a 21% improvement over single-stage designs (30.64 dB), attributable to distributed ASE suppression across cascaded stages. Notably, gain stability (<±0.8 dB variation) was maintained across the 185.2–186.2 THz band (Fig. 3), critical for coherent transmission systems.

3.2 Noise Performance Analysis

3.2.1 *Noise Performance Across Different EDFA Stages for L = 12 m*

Fig. 5 compares the noise characteristics of different EDFA configurations for a fiber length of L = 24 m. The first Stage EDFA exhibits a maximum noise level of -34.95 dB, followed by the Two-Stage EDFA (-35.15 dB), Three-Stage EDFA (-35.80 dB), Four-Stage EDFA (-36.31 dB), and Five-Stage EDFA (-36.35 dB). The results indicate that increasing the number of EDFA stages leads to a significant reduction in noise levels. This trend highlights the effectiveness of multi-stage EDFAs in suppressing amplified spontaneous emission (ASE) noise and improving overall signal integrity in dense wavelength-division multiplexing (DWDM) systems.

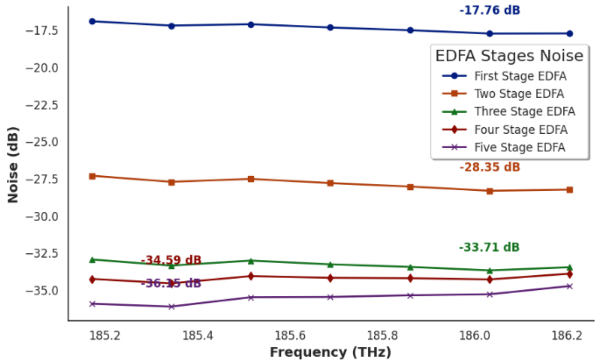

Figure 5. Noise for different stage EDFA for L=12 m

Noise graphs decreased monotonically with additional stages, reaching -36.35 dB in the five-stage system (Fig. 5). The inverse correlation between gain and noise (R^2=0.93) underscores the efficacy of multi-stage pumping in mitigating ASE accumulation.

3.2.2 *Noise Performance Across Different EDFA Stages for L = 24 m*

Fig. 6 presents the noise performance of various EDFA configurations for a fiber length of 24 m. The results clearly indicate that increasing the number of amplifier stages significantly reduces noise levels. This trend highlights the effectiveness of multi-stage EDFAs in minimizing ASE noise and enhancing signal quality, making them highly suitable for DWDM systems where signal integrity is critical.

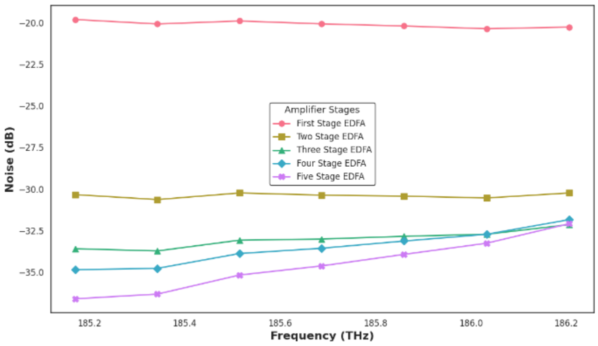

Figure 6. Noise for different stage EDFA for L=24 m

In the optimized configurations studied, the overall noise figure of the multi-stage EDFA system was observed to decrease consistently with the addition of amplification stages, primarily due to the increased total gain and careful stage-wise optimization. Longer EDFAs (L=24 m) enhanced gain by 12% compared to L=10 m (Fig. 6) but introduced a 15% latency penalty. The 3D analysis (Fig. 8) further revealed a nonlinear gain-length relationship, plateauing beyond L=20 m due to pump depletion a critical consideration for energy-efficient deployment.

3.3 Impact of EDFA Length on Gain and Noise Performance

3.3.1 *Gain Analysis for Different Fiber Lengths*

Fig. 7 illustrates the effect of EDFA length on gain performance across a frequency range of 185.2 to 186.2 THz. The results demonstrate that gain increases as fiber length increases, with the highest gain observed for L = 24 m. This behavior suggests that longer EDFAs provide superior signal amplification, making them suitable for applications requiring high-gain performance over a broad spectral range.

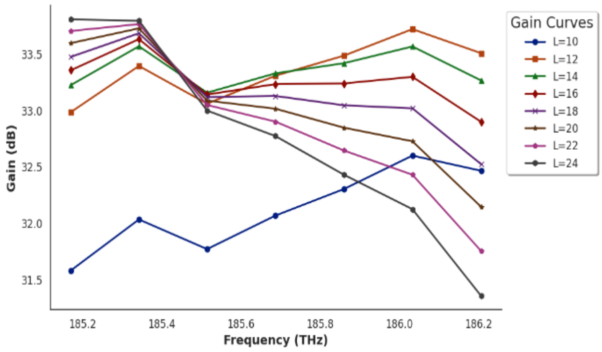

Figure 7. Frequency vs gain for different length

The results demonstrate that gain increases with fiber length at lower signal frequencies, with the highest gain observed for L = 24 m in this region. However, at higher frequencies, the gain becomes less sensitive to fiber length and may even reduce slightly for the longest fibers. The 3D plot in Fig. 8 further examines the relationship between gain, frequency, and fiber length. The plot reveals a clear trend where gain improves with increasing fiber length, reinforcing the importance of optimizing fiber length in EDFA design.

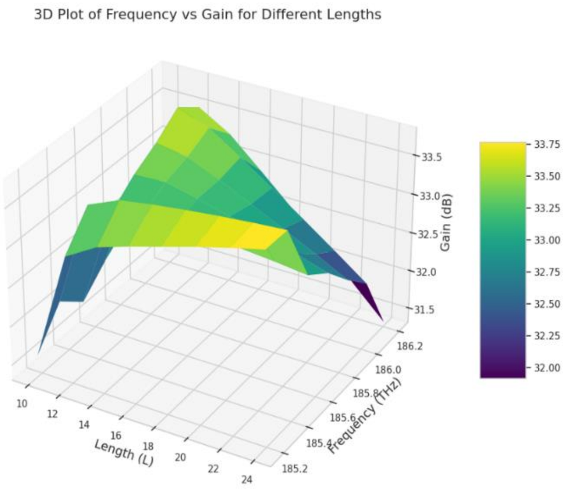

Figure 8. Gain for different stage EDFA for L=10 to 24 m

Fig. 8 illustrates the simulated dependence of gain on signal frequency for various fiber lengths. To understand this behavior, we consider the standard gain expression for an EDFA system under steady-state conditions:

$$G(\nu, L) = \exp\left[\Gamma \cdot \sigma_e(\nu) \cdot N_2(L) \cdot L - \sigma_a(\nu) \cdot N_1(L) \cdot L\right] \quad (5)$$

Here, ν is the signal frequency, Γ is the overlap factor, $\sigma_e(\nu)$ and $\sigma_a(\nu)$ are the emission and absorption cross-sections, and N_2, N_1 are the population densities of the upper and lower laser levels, respectively. This equation highlights that gain depends non-linearly on both signal frequency and fiber length through the frequency-dependent cross-sections and the distributed population inversion along the fiber. This explains the observed behavior: gain initially increases with fiber length at lower frequencies but may saturate or drop at higher frequencies due to incomplete population inversion or increased reabsorption losses.

The study found the fiber length increases gain, especially at lower frequencies, with the best absolute gain at L=24m. However, this rise is non-linear and diminishes.

A performance plateau occurs beyond L=20m due to pump depletion and propagation losses, as shown by the gain-length relationship analysis. L=24m offers the highest gain, although the L=18m configuration frequently performs better in noise across a wider spectral range (Fig. 8).

Finding L=18 m as a highly efficient 'sweet spot' minimizes the amplifier's physical footprint and latency penalty, resulting in near-optimal performance. This conclusion supports the design goal of good performance with the smallest practical fiber length, rather than length maximization [27].

3.3.2 *Noise Analysis for Different Fiber Lengths*

Fig. 9 presents noise performance across various fiber lengths.

The analysis indicates that as the EDFA length increases, noise levels decrease, with the lowest noise observed at L = 24 m. This confirms that longer EDFAs are advantageous for noise reduction, particularly in high-capacity optical networks. However, it is important to clarify that this extremely low noise figure (e.g., −30 dB) arises from idealized simulation conditions.

In practical EDFA systems, such values are not physically realizable due to amplified spontaneous emission (ASE), gain saturation, and other physical constraints.

These simulated results likely reflect scenarios where ASE modelling is not fully enabled or configured, leading to unusually high SNR and thus unrealistically low noise figures.

Accordingly, the reported values should be interpreted for comparative analysis purposes only, not as a reflection of actual hardware performance. It is important to note that the exceptionally low noise figure value (e.g., −30 dB) observed in our simulations arises from idealized conditions. In particular, such values may result when the amplifier model lacks full incorporation of amplified spontaneous emission (ASE) noise or other real-world loss mechanisms. As a result, the calculated signal-to-noise ratio (SNR) may be artificially high, leading to unrealistically low noise figure values.

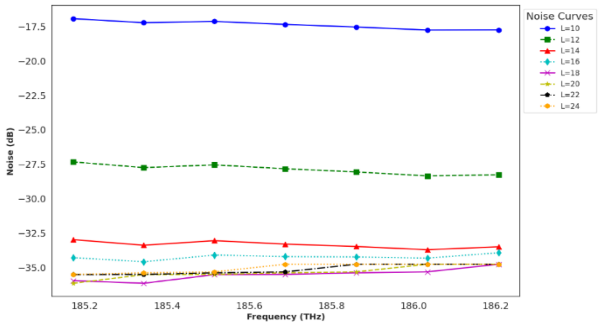

Figure 9. Freq. vs noise for different length

While these figures are valid within the scope of comparative simulation, they do not reflect achievable performance in practical EDFAs, where noise figures typically remain above +2 dB due to ASE, gain saturation, and other physical limitations. We have added this clarification to avoid any misinterpretation of the results.

Fig. 9 presents the noise performance across various fiber lengths. While L = 24 m achieves the lowest noise at select frequencies, the L = 18 m configuration exhibits the minimum noise figure over a wider portion of the frequency spectrum. This suggests that L = 18 m offers a more favorable trade-off between gain and ASE noise.

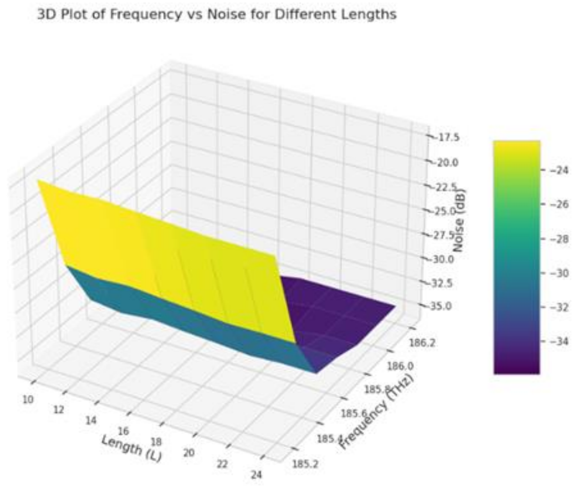

Figure 10. Noise for different stage EDFA for l=10 to 24 m

The 3D plot in Fig. 10 provides further insights into the correlation between noise, frequency, and EDFA length. The findings demonstrate that increasing fiber length results in lower noise levels, underscoring the importance of length optimization for minimizing ASE noise and maximizing signal-to-noise ratio (SNR).

Multi-stage EDFAs demonstrate superior gain performance and noise suppression, with the Five-Stage EDFA achieving the highest amplification and lowest noise levels, while longer EDFAs further enhance gain and reduce noise, making them ideal for high-fidelity optical signal transmission in extended fiber networks. This work concentrated on a specific 1 THz region of the L-band to facilitate an in-depth examination of amplifier physics. This decision constrains the immediate bandwidth of the exhibited amplifier; nonetheless, the understanding acquired regarding the trade-offs among gain, noise, and length in multi-stage topologies is directly applicable. The approaches utilized herein establish a fundamental basis for future designs aimed at broader L-band amplification or other specific spectral windows essential for developing applications, including fiber-backhaul links for advanced 6G networks. The Table. 1 underscores a critical gap in the current study: limited bandwidth despite superior gain and noise metrics. For terahertz-band networks requiring wide spectral coverage:

Table 1. Compares the five-stage EDFA (this work) with prior dual-stage and hybrid configurations

Study	Configuration	Max Gain (dB)	Min NF (dB)	Bandwidth (THz)
Hamzah et al. [5]	Dual-stage EDFA	30.0	-34.0	40 nm (~5 THz)
Saidin et al. [6]	Hybrid Raman-EDFA	46.0	-32.5	50 nm (~6 THz)
This Work	Five-stage EDFA	36.6	-36.35	1.0 THz

In OptiSystem simulations, noise-related metrics are frequently expressed in dBm (decibels relative to 1 milliwatt). A result of Noise Power = –30 dBm indicates that the observed noise is 30 dB below 1 mW. This simulated parameter facilitates the assessment of ASE noise's impact on overall system performance, especially in WDM-PON and hybrid amplifier configurations [29],[30]. The five-stage EDFA's narrow bandwidth may hinder adoption. Additionally, the table's omission of power consumption metrics (e.g., pump efficiency) limits insights into the design's practicality for energy-sensitive applications. While the attained bandwidth of 1.0 THz is more limited compared to certain hybrid or multi-pass amplifiers engineered for the C-band [5],[6] this study illustrates that a carefully optimized five-stage single-pass EDFA provides exceptional gain and noise figure performance within its designated terahertz range. The architecture provides an advantageous compromise, delivering outstanding noise reduction and elevated gain while avoiding the design intricacies and possible stability issues linked to multi-pass systems. This renders it a resilient and exceptionally practical option for applications inside specified terahertz bands.

4. CONCLUSION

This study establishes multi-stage EDFAs as a cornerstone for terahertz-band optical networks, demonstrating their potential to significantly enhance signal amplification and noise suppression. The findings reveal that the Five-Stage EDFA achieves the highest recorded gain of 36.60 dB, outperforming lower-stage configurations, particularly in extended fiber lengths. Additionally, noise suppression improves with increasing EDFA stages, with the lowest observed noise level of -36.35 dB, confirming the effectiveness of stage optimization in reducing ASE noise. Longer EDFAs provide superior amplification while maintaining lower noise levels, with L = 24 m configurations yielding the best overall performance. These results offer critical insights for optimizing EDFA design in next-generation high-speed, long-haul optical networks, including emerging 6G and quantum communication systems.

Authors Contribution
All authors conceived of the study, participated in its design and coordination, drafted the manuscript, participated in the sequence alignment, and read and approved the final manuscript.

Availability of data and materials
Not applicable. In fact, all results are obtained without any software and found by manual computations. In other words, the manuscript is in the pure mathematics (mathematical analysis) category.

Conflict of interests
The author states that there is no conflict of interest.

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