ERBIUM-DOPED FIBER AMPLIFIER: A BRIEF REVIEW

M. Al-Rawi

Bandung Institute of Technology, Bandung, Indonesia
e-mail: muhrawi@yahoo.com

Optical amplifiers known as erbium-doped fiber amplifiers use doped optical fiber as a gain medium. Fiber lasers are connected to them. Through interaction with the doping ions, a signal is amplified after being multiplexed into the doped fiber along with a pump laser. One of the main draws of erbium-doped fiber amplifiers is their wide gain bandwidth, which is usually tens of nanometers. This is more than enough to amplify data channels with the highest data rates without causing any gain narrowing effects. The technique known as wavelength division multiplexing allows for the simultaneous amplification of numerous data channels at various wavelengths within the gain region using a single erbium-doped fiber amplifier. The paper underscores the importance of understanding and harnessing the principles of such amplification in various dynamic optical landscapes.

Keywords: erbium-doped fiber amplifier, development, applications.

Received 21.09.2025; Received in revised form 06.11.2025; Accepted 10.12.2025

1. Introduction

1.1 Fundamental concept of erbium-doped fiber amplifier (EDFA)

In fiber-optic communication systems, an EDFA is a device that increases the intensity of optical signals. By directly enhancing the optical signals without requiring electrical conversion, the amplification in EDFA in optical fiber communication greatly increases efficiency and lowers costs. Fiber attenuation, connectivity losses, and fiber splicing losses are some of the factors that cause losses in optical signals when they travel long distances. In the past, the optical signal had to be transformed into an electrical signal, amplified, and then transformed back into an optical signal to overcome these losses. This was a difficult and expensive procedure. This procedure was completely changed by the development of optical amplifiers, which allowed optical signals to be directly amplified.

Fiber Raman and Brillouin amplifiers, semiconductor optical amplifiers (SOA), and EDFAs are among the various varieties of fiber optic amplifiers. The most commonly used wavelength division multiplexing (WDM) system among these optical amplifier types is EDFA. It directly boosts the signals by using the erbium-doped fiber as an optical amplification medium. Erbium ions, responsible for the amplification, are specifically embedded into the EDFA fiber. Nowadays, long-distance optical communication often uses EDFA to make up for fiber loss. Its ability to easily integrate with WDM technology and amplify multiple optical signals at once is its most crucial feature. It is typically utilized in the C and L bands, which are roughly between 1530 and 1565 nm. However, as shown in Fig.1, EDFAs are unable to amplify wavelengths shorter than 1525 nm because of high attenuation.

EDFA's fundamental components are a WDM combiner, a pump laser, and a length of erbium-doped fiber (EDF). For the signal and pump wavelengths to propagate through the EDF simultaneously, the WDM combiner is used. A more thorough schematic diagram of EDFA is displayed in Fig 2.

An EDFA amplifier receives an optical signal from the input, such as a signal at 1550 nm. Using a WDM device, a 980 nm pump laser and a 1550 nm signal are combined, and both travel through a section of fiber doped with erbium ions. The erbium-doped fiber serves as an optical amplification medium in EDFA, as was previously mentioned. Interaction with the doping Erbium ions amplifies the signal at 1550 nm. By doing this, a weak optical signal is amplified to a higher power, increasing its strength. The working principle of an EDFA amplifier is to excite erbium ions inside the fiber using a pump laser. These excited ions release more photons in response to stimulation from the incoming optical signal, which intensifies the signal.

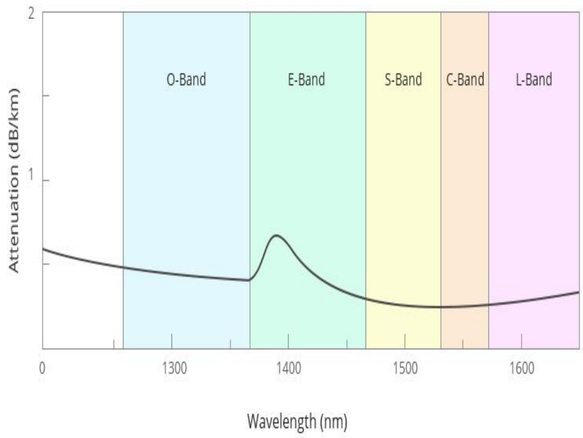

Fig.1. Optical fiber attenuation & wavelength.

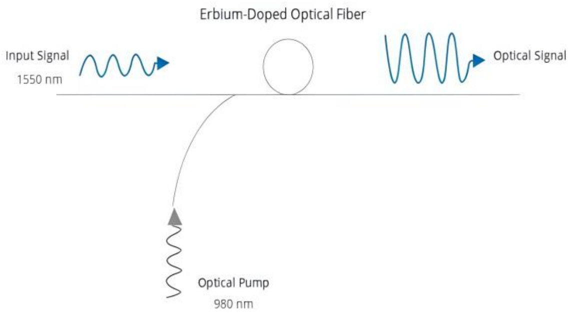

Fig. 2. Working principle of EDFA.

In conclusion, an EDFA amplifies optical signals by means of stimulated emission in an erbium-doped fiber. Erbium ions in the fiber are excited by the pump laser, and when incoming signals excite these ions, more photons are released, intensifying the initial signals. In order to compensate for signal attenuation, this procedure is essential in long-distance optical communication systems.

1.2. Types of EDFA for dense wavelength division multiplexing (DWDM) Connectivity

1.2.1. Booster amplifier

In the transmission domain of a communication link, a booster amplifier serves a crucial function by augmenting the intensity of the signal channels emanating from the transmitter to a level suitable for propagation within the fiber link. Whilst its utilization is not always necessary in single-channel links, it plays an indispensable role in DWDM links, where the multiplexer diminishes the signal channels' strength. This device exhibits high input power, high output power, and moderate optical amplification.

1.2.2. In-line amplifier

In a DWDM link, an in-line amplifier is typically placed at intermediate points along the transmission link to compensate for distribution losses and fiber transmission. On the primary optical link, the in-line EDFA is intended for optical amplification between two network nodes. To guarantee that the optical signal level stays above the noise floor, in-line EDFAs are positioned every 80–100 km. It has a low noise figure, high output power, high optical gain, and medium to low input power.

1.2.3. Pre-amplifier

A DWDM link's receiving end is where the pre-amplifier EDFA functions. Losses in a demultiplexer close to the optical receiver are compensated for by the pre-amplifier. Pre-amplifier EDFA, which is positioned before the receiver end of the DWDM link, improves the sensitivity of the receiver by raising the signal level prior to photon detection in an ultralong-haul system. Its output power is medium, its gain is medium, and its input power is relatively low.

1.3. Applications of EDFA

1.3.1. Data center interconnects

Large volumes of data exchange are handled by modern data centers. EDFAs are essential for data center interconnects because they guarantee low latency and high bandwidth connections between data centers. This meets the requirements of great data transmission.

1.3.2. Long-haul trunk communications

Communications in long-distance fiber optic systems must traverse hundreds or even thousands of kilometers. When positioned at intermediate nodes along long-distance fiber links, EDFAs function as repeater amplifiers. They ensure that the signal keeps its strength and quality over extended distances by efficiently compensating for signal attenuation.

1.3.3. Fiber optic local area network (LAN)

Erbium-doped fiber amplifiers can guarantee steady signal transmission in the local area network (LAN) to meet the requirements of multiple users accessing the network at once by boosting optical signals. LANs can use erbium-doped fiber amplifiers as a distribution compensator. It can expand the number of optical nodes and serve a larger user base.

1.3.4. Cable television (CATV) distribution network

Signals in a cable television distribution network (CATV) must be able to reach a large area. When connected after the optical transmitter's light source, an erbium-doped fiber amplifier can be used as a power amplifier to boost the signal. It guarantees that signals can reach more locations and offer more customers high-quality cable TV services.

2. Literature survey

A novel method known as the dual-stage quadruple pass (DSQP) with filters was used to demonstrate a high-gain and low-noise-figure (NF) erbium-doped fiber amplifier (EDFA). As the signal passes through the DSQP amplifier, an effective amplification takes place at the wavelength of 1550 nm. In the first and second stage amplifiers, the maximum gain of 62.56 dB and the lowest noise figure of 3.98 dB were attained with input signal power of −50 dBm and pump powers of 10 and 165mW, respectively [1].

The authors of the paper [2] propose and give deep theoretical descriptions of EDFA. The aim of this paper is to comprehend and validate the fundamentals of lasers and amplifications in EDFA, as well as how a novice in this field can conceptualize the phenomenon of lasers and amplifiers. When a signal travels through the Er^{3+}-doped core, it is amplified by the effects of pumping, absorption, stimulating, and spontaneous emission. While the spontaneous emission will happen at a variety of wavelengths, the stimulated emission will happen precisely at the same wavelength as the previous signal. Various models were put forth, each with a unique harmonization to the experimental findings. These pre-existing models are used in many experiments, but because so many parameters influence the results, they all deviate from the precise results and add complexity and misunderstanding of the actual phenomena.

Gain and the Amplified Spontaneous Emission (ASE) noise figure are evaluated in the paper [3] based on various EDFA and input signal parameters that are simulated in a 10 Gbit/s single channel fiber optic transmission system with a wavelength of 1550 nm. The goal is to determine the best pumping laser parameters for the longest transmission line possible with a maximum Bit Error Rate (BER) of 10^{-9}. The obtained results demonstrate that the EDFA amplification is dependent on multiple parameters at the same time, including the erbium-doped fiber length, pump laser configurations and directions, input signal power and wavelength. Additionally, the paper describes the implementation of a 10 Gbit/s 16 channel DWDM transmission system in the C-Band transmission window with 50 GHz channel spacing, NRZ-OOK modulation format, and an in-line EDFA with both co-propagation (980 nm) and counter-propagation (1480 nm) pump laser configuration.

In the paper [4], various EDFA pumping schemes are studied and analyzed. The analysis is made for high pump power 200mW to 600mW. Standard Erbium Doped Fiber of length 16.2m is used. Input signal power is set at -34dBm at 1550nm. Output power calculated is in the range of 15 to 25dBm, while the noise figure varied between 4.37 to 7.24 dBm. Among the different pumping methods, it is found that bi-directional pumping method shows best results.

In the work [5], various pumping techniques in EDFA are examined and evaluated. The 200–600 mW high pump power is the basis for the analysis section. The Standard Erbium Doped Fiber has a length of 16point 2 meters. At 1550 nm, the input signal power maximum range is set at -34 dBm. Although the noise figure varied between 4.37 and 7.24 dBm, the output power range is 15 to 25 dBm. It is evident from the different pumping schemes that the bi-directional pumping method produces the best outcomes.

Free Space Optics Systems (FSO), one of the best solutions for the optical communication environment, are proposed in the paper [6]. The goal is to create a new, modified WDM transmitter that uses an EDFA to operate for 16 channel multiple users. When slicing in WDM systems, the output power will record 28.4mw (14.54 dBm) as measured by the optical power meter, while the transmitter channel at frequency 1558 nm and chip spacing 0.8 nm has power equal to -23.5 dBm. Additionally, by employing the NRZ modulation format, the spectrum-sliced WDM channel operating at high data rates, like 1 Gbps, has transmitted signals over 300 kilometers without any interference, even though the input power is generated by a CW laser.

The primary choice in the work [7] is to implement an EDFA within the C-band. MATLAB programming is used to reenact the exploratory gain and commotion figure at each length and siphon control variation. In order to trigger different contributions at different wavelengths in the range of 1538 to 1565 nm, the EDFA optical intensifier is presented in the WDM plan.

One of the turning points in the development of optical access networks is the Next-Generation Passive Optical Network Stage 2 (NG-PON2), which has a minimum upstream/downstream capacity of 40 Gbps (see paper [8]). The implementation of optical amplifiers is necessary to counteract the transmission line's power degradation. The performance of hybrid optical amplifiers and EDFA boosters used in TWDM-PON systems based on NG-PON2 is to be examined in this paper [8]. Eight channels, each with a channel space of 100 GHz, and a data speed of 80 Gbps were used in our work. Using a 60 km optical link and a hybrid optical amplifier (HOA) and EDFA, this simulation was conducted. The variation of optical network unit (ONU) and amplifiers serves as the foundation for performance analysis. According to the findings, the transmission line, employing EDFA, has the best value downstream, with a received power of -19.184 dBm, a Q Factor of 7.975, and a BER of 5.852 x 10-16. With a received power value of 9.025 dBm, a Q Factor of 69.64, and a BER of 0, a hybrid optical amplifier produced the best results in upstream transmission. Implementing the optical amplifier on TWDM-PON systems based on NG-PON2 improved system performance.

The system performance of mode division multiplexing applications is described in the paper [9]. A ring profile-based multi-mode erbium-doped fiber amplifier with a minimum support of ten vortex spatial modes was used as the amplification method. The vortex lens, whose input is stimulated by a spatial laser source, configures and produces the vortex modes. The linear combination of LP modes can be used to process the vortex mode property. Spiral propagation in nature was the outcome of twisting the vortex modes' phase distribution. The vortex mode offers little difference among the higher-order modes and belongs to the same group as the orbital angular momentum modes. By using this method, the suggested system promises uniform gain distributions, minimal crosstalk, and effective vortex mode propagation at a higher data rate. In addition to their corresponding vortex modes being examined, the generated modes were categorized as LP01, LP11, LP21, LP31, LP41, LP12, LP13, LP14, LP02, and LP03.

A novel design of micro-structured core erbium-doped few-mode fiber for use as an optical amplifier in mode-division multiplexing is demonstrated and evaluated by the authors in the work [10]. This idea is put forth in order to better regulate the Er^{3+} ion distribution in the core region, which will enable the adjustment of the overall differential modal gains among the various signal modes. Ten modes in the C-band are guided by 19 erbium-doped inclusions embedded in a pedestal geometry in the design that is being presented here. To achieve equalized amplification of all signal modes, it has undergone numerical optimization. To shape the signal and pump beams, the fiber has been implemented and coupled with specially designed dual-wavelength mode multiplexers that use multi-plane light conversion. Finally, an experimental evaluation of the amplification properties has been conducted.

Gain-managed nonlinear (GMN) amplification of femtosecond pulses in an EDFA is first experimentally demonstrated in [11]. The authors of this paper used two distinct seed sources and operated at wavelengths of 1530 and 1560 nm to study the GMN amplification. Broadband output spectra covering the whole C- and L-bands (1530–1620 nm) were acquired. The study demonstrates that, unlike Yb-doped fiber amplifiers, selecting a seed wavelength at the short-wave edge of the amplifier's gain bandwidth is not essential. A seed positioned at a wavelength of 1560 nm can also be used to accomplish effective and wide-band GMN amplification.

In order to balance accuracy and computational efficiency, the authors of the paper [12] suggest a polynomial regression model for real-time EDFA noise figure estimation. To ensure robustness against measurement noise and dataset variations, the model fits a multivariate polynomial function to the measured EDFA noise figure data using Generalized Least Square (GLS) regression. The suggested approach achieves prediction errors within the measurement uncertainty of Optical Spectrum Analyzers (OSAs) when compared to experimental measurements from several EDFAs. Additionally, the model outperforms analytical models and requires a lot less data than deep-learning techniques, exhibiting strong generalization across various EDFA architectures. Analysis of computational efficiency reveals that the model is appropriate for real-time digital-twin applications in optical networks because the inference time is less than 0–2 ms per evaluation. In order to improve performance in high-variance spectral regions, future research will investigate hybrid modeling approaches that combine machine learning (ML) and physics-based regression.

These findings demonstrate the potential of lightweight polynomial regression models as a substitute for intricate machine learning-based solutions, allowing for the effective and scalable prediction of EDFA performance for next-generation optical networks.

Using a Genetic Algorithm (GA) for multi-objective optimization of gain, noise figure (NF), and differential modal gain (DMG) across multiple modes, an optimized design for a Few-Mode Erbium-Doped Fiber Amplifier (FM-EDFA) is presented in [13]. In order to accommodate four mode groups, the GA investigated a three-layer erbium doping profile structure. The results showed that low DMG, low NF, and constant high gain across modes—all necessary for long-haul space-division multiplexing (SDM) systems—could be achieved with an optimized two-layer configuration. The FM-EDFA performance under various doping profiles was confirmed by MATLAB simulations, which showed a strong balance of gain, DMG, and NF for multimode amplification. With stable, consistent amplification, this optimized FM-EDFA model facilitates high-capacity SDM transmission and provides important information for designing effective amplifiers for next-generation optical networks.

With an emphasis on ESA effects, the paper [14] examines the spectroscopic characteristics of EDFs in ternary $AlPO_4$–SiO_2 glass hosts, phosphosilicate and aluminosilicate. With a focus on silica-based glass hosts with customized fiber core material compositions, the authors examine the state-of-the-art for extended L-band EDFAs in single-stage amplification. There is discussion of several new co-dopants, including ytterbium (Yb), cerium (Ce), and yttrium (Y). Additionally, the authors investigate the optimization of amplification schemes, such as single-pass and double-pass configurations, and pump wavelengths. Additionally, the study discusses the effects of radiation and temperature on L-band EDFAs, highlighting the potential of radiation-resistant EDFAs to advance optical communications based in aerospace.

3. Summary

Erbium-doped fiber amplifiers, one of the most important and complex technologies in the field of optical communication systems, were the specific focus of this investigation. The paper provided a description of this technology's nature. The article also gave a succinct summary of some nearly recent studies on the technology mentioned.

References

1. **Bouzid, B.** High-gain and low-noise-figure erbium-doped fiber amplifier employing dual stage quadruple pass technique // Optical Review. – 2010. - Vol. 17. – P. 100 – 102. doi: 10.1007/s10043-010-0018-3.

2. **Bouzid, B.** Theoretical analysis of erbium doped fiber amplifier / B. Bouzid // 2011 Saudi International Electronics, Communications and Photonics Conference (SIECPC). – Riyadh, Saudi Arabia, 2011. P. 1 – 5. doi: 10.1109/SIECPC.2011.5876989.

3. **Putrina, J.** Evaluation of Erbium Doped Fiber Amplifier application in fiber optics transmission systems / J. Putrina, V. Bobrovs // 2016 Progress in Electromagnetic Research Symposium (PIERS). – Shanghai, China, 2016. – P. 3796 – 3802. doi: 10.1109/PIERS.2016.7735428.

4. **Rahim, M.** Study of Pumping Methods in Erbium Doped Fiber Amplifier (EDFA) / M. Rahim et al. // International Journal of Engineering Research. – 2017. – Vol. 6, No. 8. – P. 261 – 264.
doi: 10.17577/IJERTV6IS080128.

5. **Khatoon, T.** Different Pumping Methods in Erbium Doped Optical Amplifier (EDFA) / T. Khatoon // International Journal of Emerging Technologies and Innovative Research. – 2019. – Vol. 6, Issue 6. – P. 992 – 997. ISSN 2349-5162.

6. **Aldouri, M. Y.** EDFA Gain Evaluation in WDM Transmitting System of the Free

Space Optics FSO / M. Y. Aldouri, M. Mahdi, A. M. Saeed // American Scientific Research Journal for Engineering, Technology, and Sciences. – 2019. – Vol. 54, No. 1. – P. 122 – 130.

7. **Alsharfa, R.** Design and Analysis of Erbium Doped Fiber Amplifier for Optical Communication Network / R. Alsharfa // IOP Conference Series: Materials Science and Engineering. – 2019. – Vol. 518, Issue.5. doi: 10.1088/1757-899X/518/5/052024.

8. **Bagas, R.** Performance analysis of erbium-doped fiber amplifier (EDFA) and hybrid optical amplifier in NG-PON2 based on TWDM-PON system / R. Bagas, et al. // IOP Conference Series: Materials Science and Engineering. – 2020. – Vol. 982.

9. **Vigneswaran, D.** System investigations of few-mode erbium-doped fiber amplifier (FM-EDFA) for vortex mode amplifications / D. Vigneswaran, et al. // Journal of Computational Electronics. – 2021. – Vol. 20, Issue. 4. – P. 1549 – 1559. doi: 10.1007/s10825-021-01721-8.

10. **Trinel, J.** Few-mode erbium-doped fiber amplifier based on a multi-inclusions core optical fiber / J. Trinel, et al. // Optics Express. – 2023. – Vol. 31, Issue 3. – P. 4444 – 4453. doi: 10.1364/OE.473902.

11. **Krakowski, M**. Gain-managed nonlinear amplification in an erbium-doped fiber / M. Krakowski, et al. // Optics Express. – 2024. – Vol. 32, Issue 27. – P. 48815 – 48823. doi: 10.1364/OE.543377

12. **Rocco, D**. Polynomial Modeling of Noise Figure in Erbium-Doped Fiber Amplifiers / D. Rocco, et al. // Fibers. – 2025. – Vol. 13, Issue 3. doi: 10.3390/fib13030034.

13. **Rym, R.** Optimizing few-mode erbium-doped fiber amplifiers for high-capacity optical networks using a multi-objective optimization algorithm / R. Rym, et al. // Optical Fiber Technology. – 2025. – Vol. 93. doi: 10.1016/j.yofte.2025.104186.

14. **Zhai, Z.** Progress in Er-doped fibers for extended L-band operation of amplifiers / Z. Zhai, et al. // Optics Communications. – 2025. – Vol. 578. doi: 10.1016/j.optcom.2025.131510.