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**Mayank Bhargava**
Department of Electronics and Communication, Madhyanchal Professional University, Ratibad, Madhya Pradesh, India

**GF Ansari**
Department of Physics, Madhyanchal Professional University, Ratibad, Madhya Pradesh, India

**Vijeta Yadav**
Department of Electronics and Communication, Madhyanchal Professional University, Ratibad, Madhya Pradesh, India

**Ankit Temurnikar**
Department of Electronics and Communication, Madhyanchal Professional University, Ratibad, Madhya Pradesh, India

**Corresponding Author:**
**Mayank Bhargava**
Department of Electronics and Communication, Madhyanchal Professional University, Ratibad, Madhya Pradesh, India

# A comprehensive guide to optical amplifiers used in access and passive optical networks

**Mayank Bhargava, GF Ansari, Vijeta Yadav and Ankit Temurnikar**

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**Abstract**
Researchers have identified Optical Networks those are passive in nature (PONs) as a long-lasting solution for delivering broadband connectivity, particularly in remote areas where digital inclusion is vital for improving quality of life. To meet the growing demand for reliable and high capacity communication, it is necessary to enhance PONs with advanced features that enable multigigabit transmission rates over distances of several tens of kilometers. Traditionally, such performance has been achievable only in long-haul backbone networks, often at high cost due to reliance on optical amplifiers and other sophisticated technologies. This work presents a brief introduction of more satisfying methods of optical amplification and techniques which involves electrical & optical amplification suitable for PON deployment, with emphasis on their adaptability to specific operating conditions. The study suggests that modern PONs can integrate emerging backbone optical technologies while mitigating challenges such as cost and complexity, thereby offering a scalable and efficient platform for future broadband access networks. This paper presents a comprehensive study on prolonging the capabilities of Optical Networks those are passive in nature (PONs) to cop up with the increasing need for high-speed, wide range and error free propogation. The first part of the work explains in detail the principles of Amplification, Shaping and Timing and their effectiveness in enhancing signal quality and reach. The second part examines optical amplifiers, their operating principles, deployment strategies as well as their advantages and disadvantages in access network environments. The findings suggest that PONs can successfully integrate such backbone grade technologies to support multigigabit transmission over tens of kilometers. Moreover, it is argued that these enhancements can be achieved without significant drawbacks, aside from challenges like the elevated price of optical amplifiers, thereby ensuring scalability and sustainability for future broadband connectivity.

**Keywords:** Optical amplifiers, raman amplifiers, reamplification, reshaping, retiming, er-doped fiber amplifier, SOA

## 1. Introduction

Passive Optical Network (PON) technologies are primarily deployed in access networks [1-7] because they require minimal infrastructure in the optical link system (ODN). This is achieved through the use of single and shared optical fibers that connect subscribers to the central office (CO). PONs operate on a one point to many point (P2MP) architecture where resources are shared. However, sharing fibers introduces certain constraints for end users such as limited bandwidth availability while upstream communication demands additional control mechanisms to ensure secure transmission [8-13]. Typically signals in PONs can travel from the optical access unit (OLT) to the optical subscriber units (ONUs) over distances of up to 20 km. In practice, however this range often needs to be stretched particularly in rural regions, remote offices or distant cities. To address these requirements international standardization bodies including the International Telecommunication Union (ITU) and the Institute of Electrical and Electronics Engineers (IEEE) have proposed long reach PON remedy [14-19]. Achieving such extended coverage frequently relies on the use of optical amplifiers which enhance the signal between the optical access unit and optical subscriber units [20-32]. The following sections explore the various methods employed in the view of extending PON approach.

The concept of optical signal amplification stems from 1964 and merely three years later Elias Snitzer and his team introduced the first fiber laser. In both cases Neodymium was used as the dopant, enabling operation near the 1060 nm spectral window. However, during that period low loss optical fibers were not yet available.

When these optical fibers were synthesized in the 1970s, the commonly accessible transmission windows in silica was 850 nm, 1310 nm, 1550 nm and that window did not align with the capabilities of silica based Neodymium amplifiers. A significant breakthrough occurred in the later part of 1980s when Sir David Payne, Emmanuel Desurvire and their collaborators introduced Er-doped fiber amplifiers (EDFAs) designed specifically for the 1550 nm window [33, 34]. EDFAs revolutionized long distance and high speed communications by replacing costly electronic repeaters. A single optical amplifier could substitute dozens of repeaters and function largely independent of data rate or modulation format [35-42]. This innovation contributed to the evolution of Ethernet technology. Initially developed in the 1970s for short-range connections within offices or buildings using copper cables, Ethernet has since incorporated optical fibers, allowing deployment across local (LAN), metropolitan (MAN) and wide area networks (WAN). With the aid of optical amplifiers, wired network has further extended its reach. Interestingly, while Ethernet was once dismissed as overly simplistic, it has outlasted competing technologies of its era for instance, the Token Ring and Fiber Distributed Data Interface (FDDI) systems.

In a similar manner, optical amplifiers are gradually being introduced into networking domains that were once thought unsuitable for such advanced optical solutions. A key example is Passive Optical Networks (PONs), which were traditionally regarded as separate from high-speed, long-haul backbone infrastructures operated by global Internet providers. However, the rapid growth and popularity of PONs have highlighted the need to incorporate modern technologies into what were once considered low-cost and entirely passive systems. Current PON standards now envision transmission capacities reaching multigigabit levels with speeds up to 100 Gbit/s under serious consideration. Moreover, Ethernet-based PONs are emerging as strong contenders to replace asynchronous transfer mode (ATM) based Passive Optical Networks. In this context, optical amplifiers are expected to play a crucial role, particularly in regions like Canada, the United States, Norway and Sweden where transmission ranges often exceed the limits originally defined in earlier PON standards. This development mirrors the trajectory of Ethernet, which evolved from short-range applications to becoming a global networking backbone.

In recent years optical amplifiers have evolved significantly and offering new opportunities for Passive Optical Networks (PONs). Compact designs are now readily available and high performance Er-doped fiber amplifiers (EDFAs) can even be obtained in pluggable transceiver formats. As a result, optical amplifiers have become far more affordable with power consumption levels that are both practical and efficient. While it is true that no active component can match the simplicity of passive instruments in the same manner as optical splitters. The energy requirements of optical amplifiers and Ethernet switches are generally lower than those of optical terminals (OLTs) and optical units (ONUs). Though each new generation of OLTs and ONUs continues to improve in efficiency. For many researchers who are working in the PON field, optical amplifiers remain relatively unfamiliar, making it important to present studies like this one which aim to connect the advancements of high speed long-haul networks with PON technologies.

The scheme of this paper is as follows: Second section explains the principles of the regeneration techniques like Reamplification, Reshaping and Retiming. These techniques are used for data stream recovery after optical fiber communication. Section 3 discusses the role of optical amplifiers in telecommunications with a focus on their application in PONs and underlying operational principles. Section 4 provides final remarks.

**Reamplification, Reshaping and Retiming**

The standards for high-bandwidth passive optical access system (GPONs) outline two primary strategies for extending transmission reach. The first one relies on optical to electrical and then to optical (OEO) conversion, while the next one employs all optical signal processing combined with signal boosting. In this work the fundamental concepts of OEO based amplifiers are being explained. These amplifiers are generally classified into three types. Type-1 involves only Amplification, Type-2 involve amplification & shaping of signal, Type-3 involve amplification, shaping and timing. Although current research largely focuses on all optical amplification methods. We examine all three categories of amplifiers and Type-3 amplifiers have vital role in future xPON implementations [43-49].

In fiber optic communication systems, signal quality is primarily affected by several impairment factors. One major limitation comes from spontaneous emission amplification (ASE), introduced by photonic amplifiers. Another significant issue is pulse broadening caused by variation of group velocity with wavelength or frequency (GVD), which can typically be mitigated using passive dispersion compensation techniques. Polarization dependent group delay (PMD) also contributes to signal degradation. Additionally, nonlinear effects linked to the Kerr nonlinearity play a role, including cross-phase modulation that may introduce timing fluctuation in Wavelength-based signal combining (WDM) systems and Raman amplification, which can lead to variations in the average power across different channels [50].

The Type-1 is the most basic type of optical signal amplifier. It functions by amplifying the incoming signal and passing it directly to the output without any form of regeneration. The output message maintains the same shape, position and phase as the input. Although Type-1 amplifiers do not restore the signal quality, their simplicity offers several advantages. One key benefit is that the amplified signal remains unaffected by factors such as modulation format, data rate or other signal characteristics. As illustrated in Figure 1, the input signal may be faded but the amplifier merely increases its power level without altering its form or timing. In fact, almost all types of optical amplifiers fall under the Type-1 classification since they focus solely on amplification rather than signal reshaping or retiming.

The Type-2 amplifier operates in a more sophisticated manner compared to the Type-1 category as it not only amplifies but also reshapes the input signal. As the optical signal travels farther from the transmitter its waveform gradually deteriorates. In optical communication systems, this degradation is primarily influenced by the attenuation of optical fibers. Although significant advancements have been made in fiber manufacturing, it is still impossible to completely eliminate attenuation due to the presence of impurities and imperfections in silica fibers (as discussed in references) [51, 52]. Typically, the standard attenuation coefficients for optical fiber communication are 0.35 dB/km and 0.22 dB/km at 1310 nm and 1550 nm respectively. Another significant factor influencing signal quality is dispersion (further discussed in references) [53-55]. Dispersion generally causes distortion of the optical transmission as it travels through the fiber length, resulting in temporal broadening. This effect limits the transmission distance by reducing the signal to noise ratio, data rate and leads to incorrect interpretation of logical bits (0 or 1) at the receiver end. The Type-2 amplifier commonly known as a regenerator which addresses this issue. In this process, the incoming optical signal is first converted into an electrical form, where logical decisions are made to distinguish between binary 0s and 1s. The regenerated electrical message is then modify to an optical message and transmitted back through the fiber cable. As a result, the output signal regains its original shape and amplified power level, however its timing is not restored. It means that position of signal pulses remains unchanged, as illustrated in Figure 1.

The Type-3 amplifier extends the functionality of the Type-2 amplifier by incorporating timing (re-timing) synchronization into its operation. In this process, the input optical information is first modified to the electrical region, where it undergoes amplification and reshaping. Subsequently, the clock signal is extracted and reconstructed to restore the correct timing position of the signal pulses, typically using a comparator or similar circuit. The resulting output signal closely replicates the primary optical message that was initially transmitted through the optical link. The working principle of Type-3 amplifiers is illustrated in Figure 2, while Figure 3 presents the schematic diagram of a Long Reach Passive Optical Network (RE-PON).

Type-3 regeneration(restoration) can be implemented in different configurations: inline restoration and in-node restoration. Inline Type-3 restoration is typically utilized when the transmission range between two network endpoints surpasses the system power budget of the optical link. On the other side, in-node regeneration takes place within optical switching nodes, where optical to electrical and then to optical (OEO) restoration are commonly installed to restore signal quality [56].

Note that OEO Type-3 regenerators are dependent on the signal waveform (modulation formats). If the waveform is changed, the Type-3 regenerator must be adapted to it. A second significant limitation of Type-3 regeneration is the bit rate. The maximal bit rate for OEO Type-3 regenerators is approximately 40 Gb/s. Both problems are solved in all-optical Type-3 regenerators.

The ITU-T G.984.6 protocol established in year 2008, defines the specifications for optical reach extension in GPON (Gigabit Passive Optical Network) systems. This protocol outlines the network structure and connection attributes required for extending Gigabit Passive Optical Network transmission distances through a physical layer repeater section positioned between the Optical Line Terminal and the Optical Network Unit, utilizing an Electronic component with amplification or control capability at the far end node. The GPON reach extender allows data transmission up to 60 km and allowing a maximum division into 128 outputs [48]. In accordance with ITU-T G.984.6, there are two primary techniques for optical signal amplification. The first approach involves bidirectional optical amplification which operates on the Type-1 regeneration principle. Amplifiers implementing this method can employ technologies such as Erbium Ion Doped Fiber Amplifiers (EDFA), Raman gain device or Semiconductor based Optical Amplifiers.

The second method for signal amplification involves the use of an Optical-Electrical-Optical (OEO) regenerator, as illustrated in Figure 2. This regenerator contains two branches, each managed through diplexers to handle bidirectional transmission. In both branches, the transmitter and receiver are specifically designed for their respective wavelength bands, which necessitates converting the optical signal into a voltage-based signal. The voltage-based signal is then retrieved and transformed back into the light signal. A crucial objective of this process is the recovery of the timing pulse. In the downstream direction, this operation occurs in continuous mode, while in the upstream direction, it functions in burst mode. The ITU-T G.984.6 protocol also allows for hybrid configuration, such as employing an O/E/O regenerator downward direction and a Semiconductor Optical Signal Booster upward direction. Although all photonic Type-2 regeneration is achievable, it lacks transparency to the modulation format of the received signal [57]. Meanwhile, fully photonic Type-3 reconstruction hasn’t been standardized yet for Passive Optical Networks (PONs) but is being proposed for next generation systems [58].

Full optical Type-3 regeneration with a real function of retiming requires clock recovery, which can be achieved either electronically or all optically. The main difference between both types of retiming is that electronic functions are narrowband compared with broadband optical clock recovery [59]. Full optical Type-3 regeneration can be realized in two different ways:

1. Data driven Type-3 regenerator-nonlinear optical gate. This scheme mainly consists of an optical amplifier that is, a clock recovery block providing an unjittered short pulse clock stream, which is then modulated by a data-driven nonlinear optical gate block [50].
2. Synchronous modulation Type-3 regenerator-this technique is particularly efficient with pure soliton pulses. It consists of combining the effects of a localized “clock-driven” synchronous modulation of data, filtering and line fiber nonlinearity which results in both timing jitter reduction and amplitude stabilization (see Figure 4). The high dispersion fiber first converts the amplified pulse into a pure soliton. The filter blocks the unwanted ASE but also has an important role in stabilizing the amplitude in the regeneration span. Data are then synchronously and sinusoidally modulated through an intensity or phase modulator, driven by the recovered clock [50].

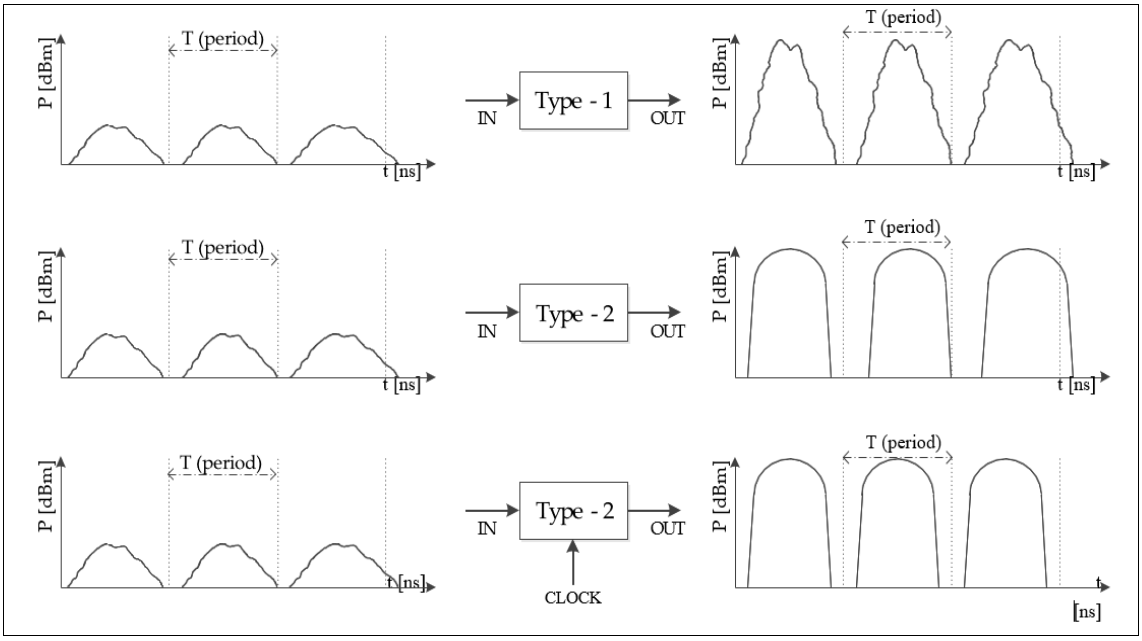


**Fig 1:** Principle of Type-1, Type-2 and Type-3.

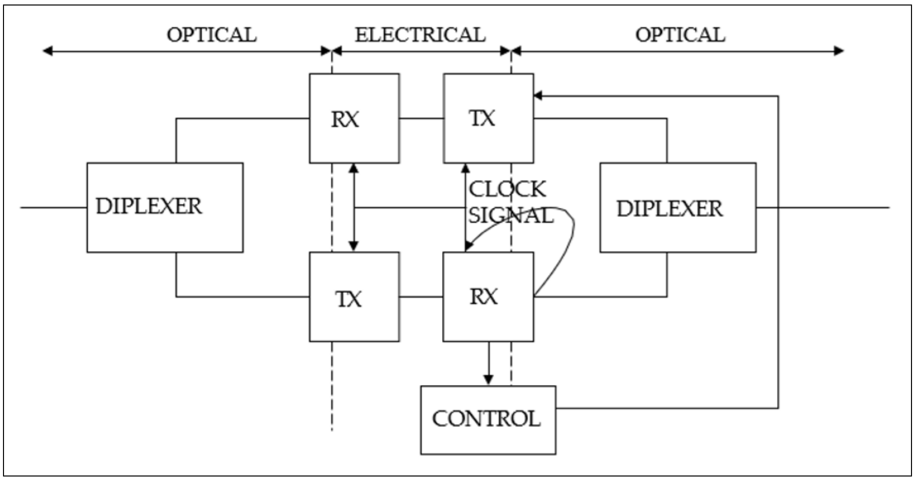


**Fig 2:** Principle of Type-3 in a reach extended passive optical network (RE-PON).

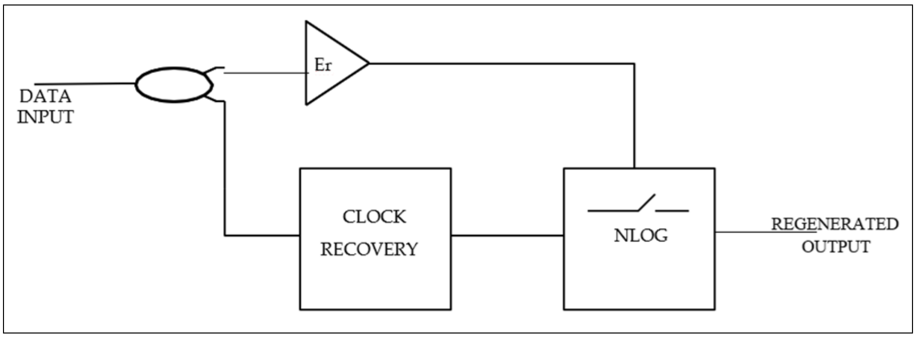


**Fig 3:** Block scheme of an RE-PON.

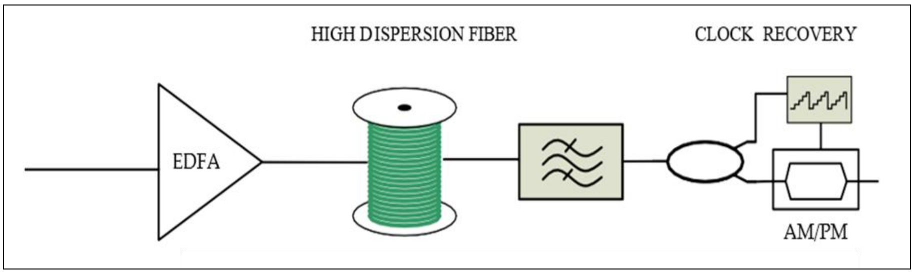


**Fig 4:** Principle of synchronous modulation optical regeneration

**Optical Amplifiers in Telecommunications Networks**

Optical amplifiers contribute significantly in all light-based communication systems and are not confined solely to long-distance networks such as submarine links. Comprehensive studies on optical amplifiers can be found in several authoritative sources [60-62] which serve as foundational references for the discussion presented below. In optical networks utilizing 1 Giga bits per sec and 10 Giga bits per sec transceivers, the typical transmission range is up to 80 kilo meters with certain duplex communication device capable of extending the reach to 120 km. While transmission over 80 kilo meters can be achieved with no error correction, longer distances necessitate the utilization of Forward Error Correction techniques to retain signal integrity. The landscape of optical communication evolved significantly with the introduction of harmonic transmission systems in 2008 [63]. By 2019, synchronous systems supporting data rates of 200 Giga bits per sec had become standard and those achieving 400 Giga bits per sec were also commercially available but these systems remain costly and typically support optical reaches confined to a couple of hundred kilometers. The emergence of advanced silicon-based digital signal processing technologies is expected to further enhance performance enabling transmission speeds up to 600 Gb/s and potentially extending optical reach to around 400 km, representing a substantial improvement over current capability.

The concept of optical amplification emerged in the era of 1960s with the first photonic amplifier being developed in the year 1964 by Scientist Elias Snitzer, who utilized neodymium as the dopant material operating within the 1060 Nano meter light region. Mr Snitzer also pioneered the creation of the first Er-doped glass laser. Subsequent experiments involving Nd(Neodymium) were conducted around 1970, though the technology was not yet mature enough for practical applications. The fundamental ideas behind these developments were later employed in the fabrication of single core optical fibers during the early 1980s at Bell Laboratories. In 1985, researchers at the Southampton University and AT&T Bell Labs successfully demonstrated erbium doped fiber amplification. The major breakthrough of this work was the discovery that erbium ions could efficiently amplify signals at 1550 Nano meter, which matches to the minimum loss transmission band of silica-based light fibers [60].

Optical amplifiers are often described as all-optical devices in contrast to optical-electrical-optical (OEO) regenerators. It is mandatory to jolt down that in submarine communication device, light amplifiers are sometimes termed as “regenerators” which can cause confusion when compared to the terminology used in terrestrial telecommunication networks. The primary benefit of optical amplifiers is their ability to simultaneously amplify multiple optical signals within a single device. This stands in stark contrast to OEO regenerators, which are limited to handling one signal at a time and require costly multiplexing and demultiplexing processes to manage multiple channels.

Optical amplifiers increase the power of light signals through induced emission, which is alike the fundamental principle used in lasers. They are usually referred to as open loop lasers. To operate a light amplifier which is energized either optically or electrically, to achieve population inversion of the dopant ions. Population inversion occurs when a greater number of particles photons in the case of light amplifiers occupy higher-lying energy states that would exist under normal conditions without energizing. These higher lying energy states are inherently not stable and eventually return to lower-energy level over a population relaxation time, which typically ranges from 1 nano sec to 1 milli sec (though other values are feasible and are analyzed in further specialized references on light amplifiers) [60].

Diagram 5 illustrates various optical amplifier configurations used in practical systems. A booster-only configuration is generally employed for relatively short distances around 150 kilo meters (Diagram 5a). A front-end amplifier setup is chosen when it is important to avoid the high optical power levels generated by boosters. In such cases, an optical filter is often required to minimize noise (Figure 5b). For Lengthier links such as 250 km, a combination of enhancer and front-end amplifier is necessary (Diagram 5c). In extended series light spans, inline amplifiers are deployed (Figure 5d). While optical filters are typically needed with preamplifiers to minimize noise, they are generally unnecessary for booster or inline repeaters. The final structures involve Raman elevating, which can extend transmission distances to approximately 350 km. However, Raman amplification requires high photonic powers (up to 1 W) due to the relatively low Raman phenomena in silica fibers, necessitating strict eye safety precautions. It is important to note that the distances mentioned are approximate and depend heavily on the actual transmission equipment, with receiver sensitivity being the most critical factor.

The general parameters of photonic booster are summarized as follows [64]:

1. **Gain:** The ratio between the output and input optical power.
2. **Gain flatness:** Ideally, the gain should remain uniform across the operating wavelength range.
3. **Saturation power:** The maximum input power the amplifier can handle without significant distortion.
4. **Saturation gain:** Indicates the energy efficiency of the amplifier.
5. **Insertion loss:** The loss introduced when the amplifier is inserted into the optical path, including when it is switched off.
6. **Bandwidth:** The spectral range over which the amplifier operates effectively.
7. **Noise figure:** Is a scale of the impact of the repeater on the signal to noise ratio (SNR).

**Temperature stability:** The ability of the amplifier to maintain performance under varying thermal conditions.

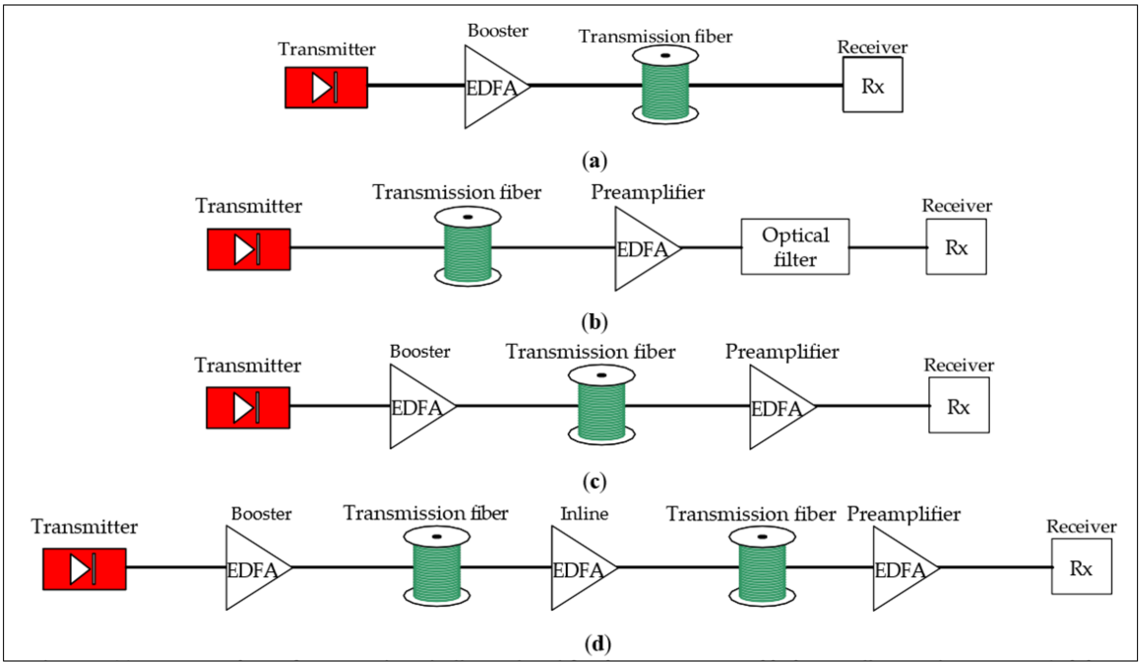


**Fig 5(a):** Booster-only configuration is typically employed for short-range optical links, usually spanning 100 to 150 kilometers. (b) preamplifier-only configuration, when it is necessary to avoid high-power boosters, (c) booster and preamplifier configuration for distances of approximately 200 km, (d) booster, inline and preamplifier configuration for longer distances (cascaded fibers).

## I. Erbium ion Doped Fiber Amplifiers

The true advancement in photonic amplification began in the era of 1980s with the commercial introduction of amplifiers utilizing rare earth doped fibers. Groundbreaking research in this area was conducted by D. Payne and E. Desurvire whose work laid the foundation for the progress of $Er^{+}$ ion Doped Fiber Amplifiers. Comprehensive discussions on EDFAs can be found in [65] while an in-depth theoretical analysis is presented in [66]. Although fiber doped with rare-earth elements had been studied since the 1960s, the fabrication technologies of that era were not advanced enough for practical deployment. Various rare-earth ions including Neodymium, Holmium, Thulium and Ytterbium can serve as dopants enabling amplification over a broad wavelength band from 500 nano meter to 3500 nano meter. However, the cost effectiveness of these amplifiers depends on the specific dopant fiber combination, as some non-silica fiber materials are challenging to manufacture and maintain.

References to the rapid and accelerated growth of internet data flow & global fiber optic web have become well known common place. Two decades ago, these networks were primarily used for telephone communication and cable television transmission. However, the true surge in data demand began with the emergence of the Global Web (www). During that period, the implementation of photonic repeaters within LAN was considered cost prohibitive but in recent years technological advancements and reduced production costs have made their deployment much more feasible and economical.

The first $Er^{+}$ ion Doped Fiber Repeater was successfully demonstrated in 1989, marking a notable progress in photonic research. The initial adoption of this innovation occurred in submarine (undersea) communication systems, where all optical amplification effectively replaced the costly and less reliable electronic repeaters. The Intercontinental Transmission networks are often recognized as the early long-range systems designed to fully exploit the advantages of $Er^{+}$ ion doped photonic amplifier, achieving commercial deployment by 1996. Subsequently, similar systems were implemented in the United States and Japan with amplifier spacing typically ranging between 30 km and 80 km depending on system design and signal requirements.

Terrestrial optical communication systems soon adopted similar technologies as their undersea counterparts, primarily to eliminate the need for electronic regenerators. Interestingly, the earliest transmission systems were designed to handle only a single communication channel. Even by the early 1990s, advanced commercial optical transport systems could accommodate up to 16 channels per fiber, each transmitting at a data speed of 2.5 Giga bits per sec, later the speed upgraded to 10 Giga bits per sec. At that time, researchers and engineers anticipated the development of systems capable of supporting up to 100 channels in the future [60].

Among all rare earth elements used in optical communication, Erbium holds the greatest significance due to its ability to amplify signals within the third wavelength window of silica fibers, commonly known as the C-band, centered around 1550-1565 nano meter. The development of $Er^{+}$ ion Doped Fiber Amplifiers termed as the starting of a new generation in optical telecommunications. Typically, EDFA placement in a transmission link is around 80 kilo meters, though in some shorter distance systems, the spacing can extend to over 200 km. This represents a major improvement compared to OEO regenerators, which required placement approximately every 10 km and could process only a single signal at a time. In contrast, EDFAs are capable of amplifying up to 100 channels within the Conventional band wavelength range. Most Dense Wavelength Division Multiplexing systems functions within this band. Furthermore, when higher capacity is required, EDFAs can be optimized for the long wavelength L-band (1565-1625 nano meter) to extend amplification capability [60].

To achieve optical gain, $Er^{+}$ ion Doped Fiber Amplifiers require optical pumping to create population inversion (as illustrated in Figure 6). Figure 6a presents the quantum state diagram of $Er^{+}$ ions, where electrons are jumped from the lower quantum state to a higher quantum state with a relatively short life span of approximately $10^{-6}$ second.

These excited electrons then transition to a metastable state with a lifetime of about 10 milliseconds, where they remain until stimulated by incoming photons, resulting in amplification through radiative emission. The energy levels of erbium are commonly described using the Russell Saunders notation, though detailed theoretical explanations are beyond the present discussion. Figure 6b provides a more detailed view, showing energy level splitting caused by spin orbit coupling and fine structural effects within the silica glass host material. From this diagram, the amplification mechanism can be understood for various spectral regions specifically, for Erbium amplifiers, the range lies between 1530 nm and 1565 nm. EDFAs can be pumped at different wavelengths, with 980 nm and 1480 nm being the most efficient. Two main pumping configurations are used in backward propelling, the pump and message propagate in opposite directions, whereas in forward pumping, both propagate in the same direction. In practice, a hybrid scheme combining both methods is often employed to achieve a more uniform gain profile along the fiber.

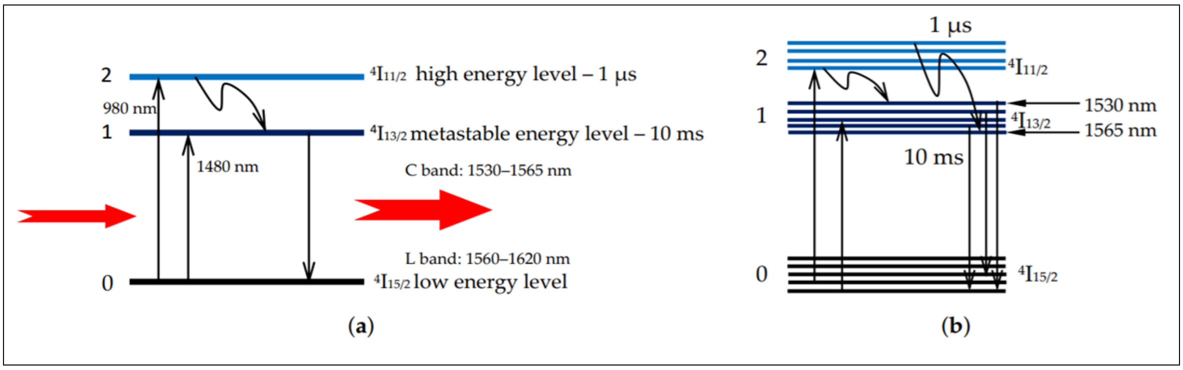


**Fig 6(a):** Schematic diagram of erbium energy levels and (b) detailed energy levels for erbium.

Like all practical devices, optical amplifiers face certain limitations in real world applications. The most significant of these is amplifier noise, commonly quantified by the noise figure (NF). This noise primarily arises from Spontaneous Emission Gain, which occurs when excited electrons abruptly return to their ground energy state, emitting unwanted photons. Although ASE can be exploited to create broadband light sources, it is generally undesirable within optical amplifiers because it degrades signal quality. The ideal theoretical noise figure for Erbium-Doped Fiber Amplifiers (EDFAs) is approximately 3 dB, whereas in practice, typical values range between 4 dB and 8 dB. Among different pumping schemes, those using 980 nm pump wavelengths tend to achieve a lower noise figure compared to 1480 nm pumping configurations.

The Erbium-Doped Fiber Amplifiers (EDFAs) discussed earlier are classified as lumped amplifiers, distinguishing them from distributed Raman amplification methods discussed in this part. However, EDFA also functions as scattred gain repeaters. Although such distributed EDFAs have been the subject of experimental research, they have not seen widespread commercial implementation.

Other rare earth element utilized in optical gain is Praseodymium. Praseodymium doped fluoride fiber repeaters also known as PDFAs for naming consistency with EDFAs are designed to magnify message within the O-band wavelength region, spanning 1260-1360 Nano meter. Unlike $Er^+$ ion doped repeaters, which operate in the C-band, these O-band amplifiers differ fundamentally in their amplification mechanism. Praseodymium (Pr) and Neodymium (Nd) function based on a four-level energy system, which typically results in slightly diminished power and enhanced noise figures as opposed to three-level systems. In a four-level system, the population inversion remains consistently positive, whereas in the three-level Erbium system, the absence of pumping such as during pump failure causes the medium to act as a strong absorber, effectively blocking signal transmission. In contrast, PDFFAs, when unpumped, neither amplify nor significantly attenuate the signal, maintaining stable transmission characteristics.

A common question arises as to why optical message should be enhanced in the relatively lossy 1310 Nano meter region, given that most long-haul communication systems operate within the C band and L-bands. The primary reasons are chromatic dispersion and the demand for huge data transmission rates. Even for 10 Gigabit Ethernet (10GE) systems, 1310 Nano meter transmitter-receivers were widely accessible and significantly more cost-effective than their 1550 Nano meter peers. The Czech Education and Scientific Network conducted several experimental studies in the 2000s using Praseodymium Doped Fluoride Fiber Amplifiers [67], particularly for enhancing the photonic reach of 10GE network interface cards (NICs). At that time, 1550 nm NIC transceivers were largely unavailable due to their high production costs. Using PDFFAs, transmission distances were successfully extended from the original 10 km to over 100 km, and nearly 200 km when combined with Raman amplification.

However, PDFFAs present certain drawbacks, primarily related to their fluoride-based fiber composition. The manufacturing process is complex because fluorine is hazardous, fluoride glass materials are hygroscopic and their mechanical strength is inferior to that of silica fibers used in EDFAs, limiting the number of capable manufacturers. Furthermore, PDFFAs exhibit higher noise levels compared to EDFAs. Despite these challenges, the issue of chromatic dispersion and data rates becomes more critical in pluggable transceivers operating at 100 Giga bits per sec and 200 Giga bits per sec. Given the large cost gap among short-reach 1310 nm and long-reach 1550 nm transceivers, PDFFAs provide a cost-effective alternative for certain applications. Additionally, Thulium-doped fiber amplifiers (TDFAs) are used in Passive Optical Networks (PONs) for messages in the 1490 Nano meter range, while Ytterbium is often employed as a co-dopant in $Er^+$ ion doped repeaters to enhance photonic output power [52].

Photonic repeaters function on the concept of stimulated emission, which is fundamentally the same process that governs laser operation. An $Er^+$ ion Doped Repeaters includes a laser enhancer diode that provides photonic radiation and a fiber doped with $Er^{+}$ ions. When the pump energy interacts with the Erbium doped fiber, amplification occurs within the C-band wavelength region. A schematic representation is provided in Figure-7. The working mechanism of the amplifier is commonly described using the "three-level" model [64].

The optical radiation generated by the laser pump is directed into an Erbium doped ($Er^{3+}$) fiber that typically extends several meters, usually between 10 and 100 meters. This radiation excites the erbium ions, causing them to move to a upper energy level, denoted as $Er^{3+}$. These ions stay in this metastable state for only a brief period typically a few milliseconds before transitioning nonradiative to the lower energy level $E_2$. Once population inversion is achieved, most erbium ions occupy the excited state, and energy is emitted in synchronization with the transmitted optical message. The ions then return to their ground state, $E_1$, within the valence band, releasing photons of identical wavelength & phase to the input message. This mechanism effectively enables temporary energy storage provided by the laser energizer.

The transmitted photonic message undergoes amplification within the C-band region, centered around 1550 nm. Both the desired signal and accompanying noise are amplified within this frequency range. Although pumping at 980 Nano meter and 1480 Nano meter is feasible, the 980 Nano meter pump is preferred because it enables a upper level of population inversion. Besides the C-band (1530-1565 Nano meter), EDFAs also operates within the L-band (1570-1625 Nano meter), differing mainly in the Erbium-doped fiber length C-band amplifiers generally require a longer fiber.

The typical gain of an EDFA ranges from 30 to 50 dB, affected by the pump laser energy & the length of the doped fiber. A higher concentration of Erbium ions results in increased energy transitions and more frequent stimulated emissions, thereby enhancing amplifier gain. Amplification depends on the level of population inversion produced by the pump laser. When the light message power rises or the pump energy drops, the inversion level lowers down, leading to reduced amplification and this phenomenon is termed as "saturation". EDFAs generally operate below this saturation level to limit spontaneous and amplified spontaneous emission (ASE), an effect known as "gain compression" [64].

$Er^{+}$ ions Doped Fiber Amplifiers are commonly used light amplifiers because of several notable advantages. They operate as fully optical systems and provide a high gain of about 30-50 dB with a decreased noise figure ranging between 4 dB and 6 dB. Their performance is independent of polarization and the output signal maintains the same phase and frequency as the input. EDFAs also offer efficient energy conversion, transferring nearly 50% of pump power to signal power. When unpumped, such as during a power outage, they function as optical shutters. Additionally, they have a broad operating range and can amplify a huge spectral bandwidth around 80 Nano meter within the 1550 Nano meter region, maintaining a relatively uniform gain that can be further optimized with gain equalizers. These characteristics make EDFAs highly suitable for long-distance optical communication applications.

Despite their advantages, EDFAs also have some limitations [64]. They produce amplified noise (ASE), leading to output noise even in the absence of an input signal. Flat-top filters are required for wavelength division multiplexing (WDM) systems. EDFAs cannot operate in the O-band and face challenges in miniaturization and integration with semiconductor devices. Furthermore, gain saturation remains a notable drawback in their performance.

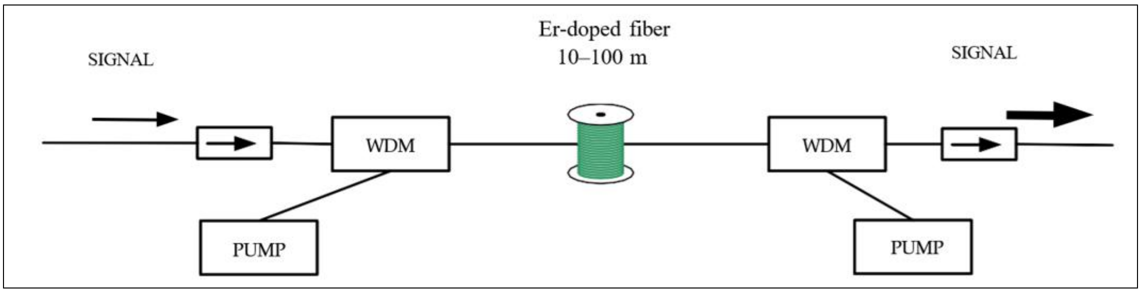


**Fig 7:** Schematic diagram of an erbium-doped fiber amplifier (EDFA) with backward and forward pumping.

**II. Semiconductor Photonic Amplifiers-SOAs**

Semiconductor Photonic Amplifiers represent another viable technology for optical signal amplification and data transmission in modern communication systems. A comprehensive overview of their development and applications can be found in [68]. Research on SOAs dates back to the 1960s, coinciding with the invention of semiconductor lasers. Although the laser concept was first proposed in 1958, the ruby laser was demonstrated in the year 1960, paving the way for the exploration of semiconductor-based amplification. The earliest SOAs were fabricated using GaAs/AlGaAs materials, but with advancements in semiconductor technology, more sophisticated InGaAsP/InP structures were later developed. These materials enabled operation within the 1300-1600 nm wavelength range, making SOAs suitable for optical communication networks.

Semiconductor Optical Amplifiers (SOAs) play a crucial role in various optoelectronic applications, including optical data storage and fast printing systems. In case of telecommunications, photonic amplifiers were first introduced during the 1980s. However, their practical use was limited by several performance challenges. These included a relatively high noise figure, sensitivity to polarization and signal distortion issues when amplifying multiple channels simultaneously, primarily caused by nonlinear light matter effects like cross-phase modulation.

Conversely, Semiconductor Optical Amplifiers (SOAs) are engineered to function across a wide spectrum of optical wave distances, including S-band (1460-1530 nm) a spectral region where rare earth doped amplifiers based on silica host materials are ineffective. An additional advantage of SOAs is their ability to be integrated onto semiconductor chips, making them highly suitable for compact and high-speed optical systems. Owing to this versatility, SOAs are commonly utilized in 100 Gigabit Ethernet (100GE) transceivers, where four SOAs are embedded within the module, each responsible for amplifying a 25 Giga bits per sec photonic channel. Beyond amplification, photonic repeaters also function as all range photonic wavelength converters and photonic switches, further extending their utility in advanced optical communication networks [59].

The structural design of Semiconductor Optical Amplifiers (SOAs) closely resembles to Fabry-Pérot lasers (as illustrated in Diagram 8). However, the Fabry-Pérot structure is generally unsuitable for information transmission applications as it provides a limited bandwidth of less than 10 GHz. To adapt SOAs for high-speed optical communication, they are modified into travelling wave (TW) amplifiers. This transformation is achieved by minimizing reflections from the ends of the SOA through the use of antireflection (AR) coatings, which must reduce reflectivity to below 0.1% to ensure optimal performance. Additionally, alternative reflection suppression methods such as angled-facet and tilted-stripe designs have been developed to further enhance the amplifier's stability and efficiency [59].

Semiconductor Optical Amplifiers (SOAs) are compact devices that are electrically pumped, unlike EDFAs, PDFFAs or Raman amplifiers which rely on optical pumping. Their design allows for easy integration with other semiconductor components such as lasers and modulators, making them suitable for photonic integrated circuits. However, several performance limitations including elevated noise levels, reduced output power and signal polarization characteristics dependence have hindered their widespread adoption as primary optical amplifiers. Although various approaches, such as parallel, series and double pass structures have been explored to improve performance. These challenges continue to restrict large-scale deployment of SOAs in optical networks.

There are several emerging applications where Semiconductor Optical Amplifiers (SOAs) show promising potential. These include their use in wavelength conversion, optical demultiplexing where ultrahigh speed signals (such as 100 Gb/s) are divided into lower-speed tributary channels (around 10 Gb/s) and in optical clock recovery systems. Despite these advancements in research, commercial products utilizing these SOA-based technologies are not yet available in the market.

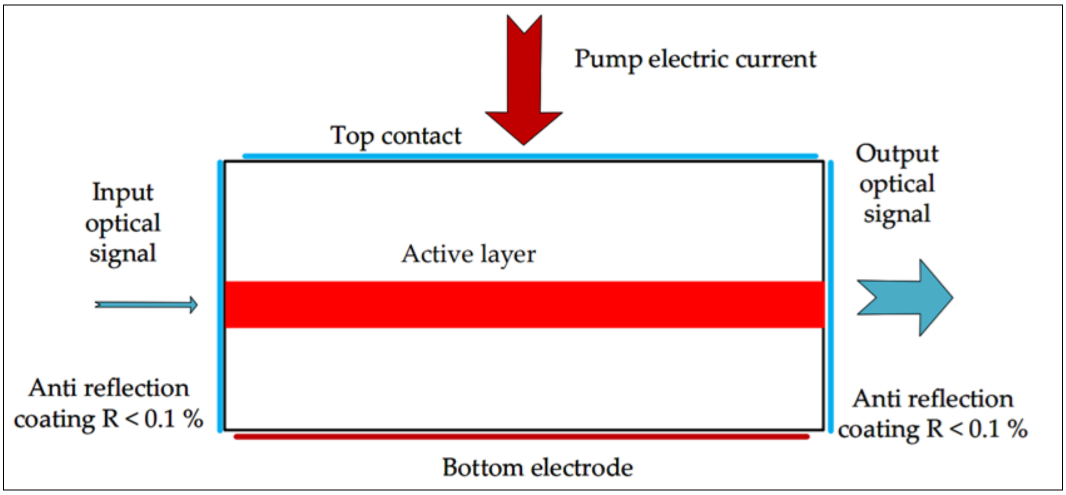


**Fig 8:** Schematic diagram of a semiconductor optical amplifier (SOA).

In Semiconductor Optical Amplifiers (SOAs), the optical gain is produced within the semiconductor structure itself, rather than in a fiber medium. Unlike optically pumped amplifiers, SOAs rely on electrical pumping, where an electric field supplies the necessary energy to achieve stimulated emission. Commonly used semiconductor materials for SOA fabrication include Gallium Arsenide, Aluminum Gallium Arsenide, Indium Gallium Arsenide, Indium Gallium Arsenide Phosphorous, Indium Aluminum Gallium Arsenide and Indium Phosphorous. These compounds exhibit high Photoelectric conversion efficiency, enabling the generation of a large count of photons during amplification. The operational concept of SOAs closely resembles that of laser photon emission, as described in [60].

Stimulated Absorption: This process initiates when photons interact with the semiconductor material, causing electrons to absorb energy and transition from the valence band to higher energy states.

Medium Excitation: In a P-N junction, excitation of the semiconductor medium occurs through energy pumping, which relies on stimulated absorption. The absorbed photon energy elevates a particle from the inner band to the outer band, provided that the photon energy overcome the bandgap energy of the semiconductor.

Population Inversion: Under appropriate forward bias conditions, a population inversion can be achieved within the diode interface, where the number of charge carrier in excited states surpasses those in lower energy levels. This condition is essential for optical amplification to occur.

Gain Generation: As stimulated emission takes place; new photons are produced through the recombination of electrons and holes. These emitted photons are coherent sharing the same wavelength, phase and polarization as the incident photons. Unlike semiconductor lasers, the resonator structure in SOAs is relatively shorter, allowing for direct amplification rather than oscillation.

Output Emission: The intensity of triggered emission relies on the strength of the incoming optical message. As the photons exit the edge of the semiconductor chip, they carry the amplified optical signal forward.

Semiconductor Optical Amplifiers (SOAs) are typically fabricated as compact chips enclosed in standard housings equipped with temperature control systems to ensure wavelength stability and enable maximum gain performance. Within the active region, a high carrier concentration results in a rise of the refractive index, which becomes greater than the surrounding cladding layer. This area functions like a photonic waveguide, efficiently directing and confining the newly generated photons during amplification [60].

**Advantages of Semiconductor Optical Amplifiers (SOAs):**

1. Operate effectively in wavelength band of 1280 Nano meter to 1600 Nano meter.
2. Provide a broad amplification bandwidth, suitable for multi-channel systems.
3. Offer a maximum optical gain of up to 30 dB.
4. Feature a compact design, allowing easy integration with lasers and other semiconductor components on a single chip.
5. Well-suited for use in all-optical communication systems.
6. Require no optical pumping, as they are electrically driven.
7. Exhibit fast gain dynamics compared to fiber-based amplifiers.
8. Cost-effective, making them attractive for large-scale applications.
9. Ideal for Passive Optical Networks (PONs) due to their compactness and efficiency.

**Disadvantages of Semiconductor Optical Amplifiers (SOAs):**

1. Exhibit a high insertion loss of around 5 dB, which can further increase when the amplifier is powered off.
2. Provide a relatively low enhancement in business versions, typically between 15 to 25 dB.
3. Show leftover polarization dependence, affecting signal uniformity.
4. Possess a increased noise figure and channel interreference, primarily resulting from abrupt effects like four-wave synthesis, with values ranging from 7-12 dB.
5. Require precise temperature control to maintain stable operation and performance.
6. Experience cross-gain modulation among multiple channels due to carrier depletion, which can distort the amplified signals.

Saturation in a Semiconductor Optical Amplifier (SOA) occurs when a input photonic message depletes the charge carriers within the active region, leading to a reduction in gain as the input power increases. The saturated output power is termed as the amplifier's gain lowers by 3 dB from its maximum point (as illustrated in Diagram 9). The adverse effects of carrier exhaustion can be mitigated through a technique known as holding beam injection or optical co-pumping, which helps stabilize carrier density and improve amplifier performance [69].

**a) Raman Amplifiers**

This widely explored method for photonic signal enhancement depends on the phenomenon of Induced Raman Scattering (SRS), which parts fundamentally from the coherent emission process that occurs in EDFAs and SOAs. In Raman scattering, the incident photons indulge with the vibrations (light phonons) of the fiber material, resulting in the production of new photons with less energy (high wave distance) the energy difference being absorbed by the fiber as vibrational energy. When the emitted light particle has less energy than the absorbed light particle, the process is termed Stokes Raman scattering. Conversely when the emitted photon has more energy, it is known as anti-Stokes Raman scattering. This phenomenon occurs spontaneously and becomes stimulated when both pump photons and signal photons propagate together within the fiber medium, similar to processes in EDFAs.

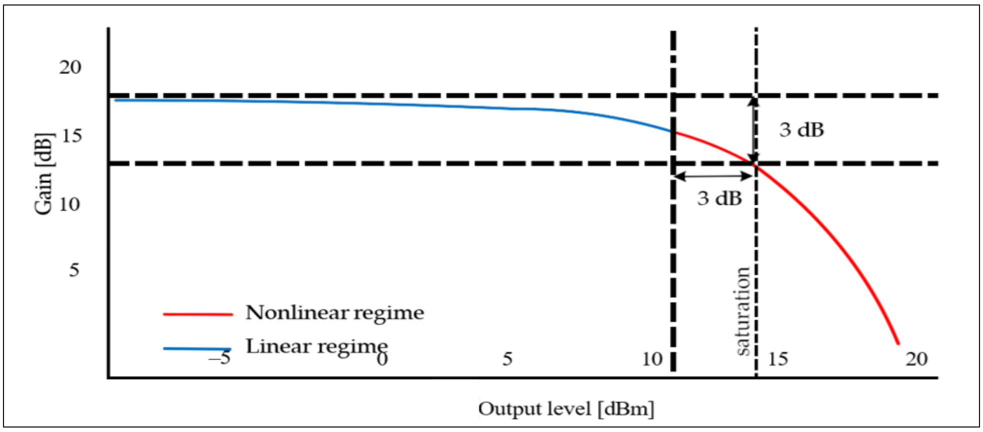


**Fig 9:** Gain dependence on the output power.

The Raman phenomena was first theoretically analysed in the 1920s and experimentally verified in year 1928 [70]. The first demonstration of Raman phenomena in optical fibers took place in 1970s, showing significant promise for optical fiber communication systems. However, the commercial adoption of Raman amplifiers was delayed as EDFAs became the dominant technology due to their simplicity and efficiency. It was not until the 2000s that Raman amplification began to integrated into long & heavy transmission systems, supported by technological improvements.

In silica fibers, the Raman effect is relatively weak, requiring higher pump powers than those used in EDFAs. Additionally, polarization dependence presents a challenge, though it can be mitigated by employing two perpendicular polarized pump sources. Another limitation is the non-uniform spectral gain, as illustrated in Figure 10. However, established gain-flattening techniques can help correct this issue [71].

The concept of Raman amplification relies on the engagement of photons and the light medium, which results in a frequency shift. Through optical pumping at specific wavelengths, photon-phonon interactions occur, transferring energy from molecular vibrations to photons, thereby generating stimulated Raman scattering within the fiber material (as shown in Figure 11). This process produces a wavelength shift of approximately 100 nm toward longer wavelengths. For example, to enhance the signals in the 1550 Nano meter band, a pump wavelength around 1450 Nano meter is used. Unlike EDFAs, Raman amplifiers do not require population excess in excited state, as the process is inelastic scattering-based. These amplifiers can give a maximum gain up to 30 dB [64] and due to their tunable pump wavelength, can operate over a very broad wavelength range, making them highly versatile for optical communication networks.

The output power of a Raman amplifier is influenced by several factors, including the pump laser's power & wave distance, the prismatic efficiency, the dimension of the optical fiber, and the mode field cross-section width (MFD). The Stimulated Raman Scattering (SRS) process occurs in both the forward and backward propagation path, allowing Raman gain enhancer to operate in two main configurations:

i) Distributed Raman Signal Booster (DRA)
ii) Lumped Raman Signal Booster (LRA)

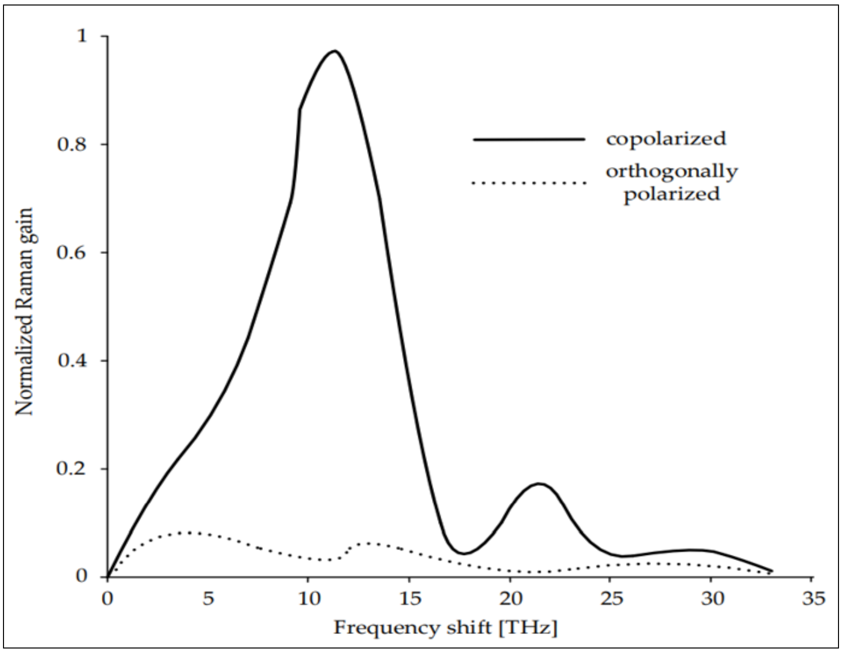


**Fig 10:** Raman gain for copolarized and orthogonally polarized pump and signal.

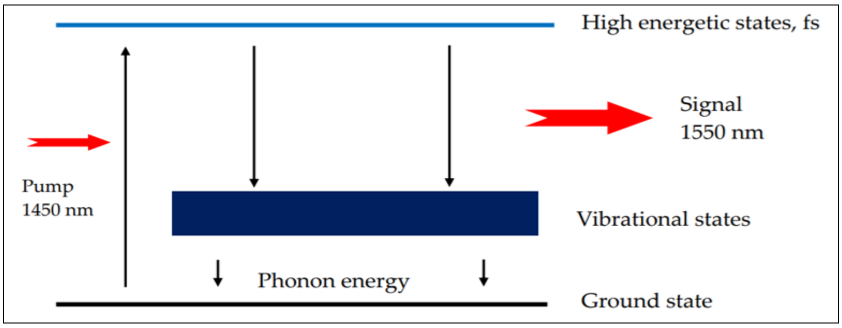


**Fig 11:** Schematic diagram of energy levels for the stimulated Raman inelastic scattering (SRS) process (silica fiber with very short high-energy-level lifetimes).

The enhancement mechanism in Raman Signal Booster is fundamentally dissimilar from EDFAs, PDFFAs or SOAs. In Raman systems, the optical transmission cable itself behave like the gain medium, making the amplification process distributed rather than confined to a discrete device. In DRA configurations, backward pumping is typically employed where the energy source is placed at receiving end of the photonic fiber. This setup ensures continuous gain along the fiber span, effectively compensating for transmission losses. DRAs are characterized by a low noise factor, high boosting and minimal nonlinear signal degradation [71].

Additionally, Lumped Raman Amplifiers (LRAs) have also been implemented in communication network, though with mild modification. In this approach, Raman boosting is combined with dispersion control fibers (DCFs). The interaction between light and the optical medium in dispersion-compensating fibers (DCFs) is significantly stronger, making Raman boosting more competent. Since Dispersion control fibers are periodically integrated along the transmission path, they are considered lumped components. By incorporating Raman pump sources into these existing DCF sections, lumped Raman amplifiers can be realized. However, with the advent of coherent transmission technologies, the use of DCFs has largely been eliminated, as chromatic dispersion compensation is now achieved digitally, removing the need for these physical components [59].

Although the Raman effect offers a broad amplification bandwidth, it also presents certain limitations, such as polarization dependence typically mitigated using pump generated depolarization techniques and small amplification factor in silica fibers (as shown in Figure 12). Consequently, high optical pump powers are required to achieve effective amplification. For instance, in CESNET experiments, pump powers exceeding 500 mW were utilized. However, operating at such high-power levels introduces serious eye safety risks, even when Laser auto shutdown (ALS) mechanisms are in place. In scenarios involving fiber breaks or Angled Fiber Connector (AFC) connectors, the ALS system may fail to detect faults promptly, increasing the hazard.

Due to these safety and operational challenges, Raman amplifiers are not commonly used in standard optical networks. Instead, they are primarily applied in specialized environments, such as submarine links or long-distance lightweight fiber spans, where extended reach is necessary. In modern Dense Wavelength Multiplexing (DWM) systems that transmit coherent photonic signals over long distances, hybrid amplification schemes combining Raman amplifiers with $Er^+$ ion Doped Fiber Amplifiers (EDFAs) are employed. This hybrid approach effectively compensates for high-attenuation fiber sections and maintains an optimal photonic message to noise ratio throughout the transmission channel.

According to certain studies [60], the interaction strength of the Raman phenomena in silica glass is relatively low, requiring a pumping unit power of up to 5 W to achieve a 30 dB enhancement. However, experimental work at CESNET revealed that even pumping unit powers below 1 Watt induced intense Rayleigh-scatter distribution (DRS), rendering such conditions impractical for stable operation. In contrast, some commercial transmission equipment manufacturers employ Raman pump powers under 500 mW, illustrating a unique scenario at the lower side of the energy spectrum. Since both Activated Raman Scattering and Activated Brillouin Scattering are nonlinear optical phenomena, a threshold photonic power is essential to initiate the amplification process.

In CESNET's experiments, Raman amplification was tested at pump power levels of 10, 50, 100, 150, 200, 250, and 300 milli Watt. The pump wave distance was approximately 1455 Nano meter, while the message wave distance was 1552.064 Nano meter, in synchronization with wave distance shift of 97 Nano meter (see Table-1). The continuous wave message from a laser diode was mixed with 50 km fiber roll. Considering a fiber attenuation about 0.18 dB/km (roughly 4% loss per kilometer), the total signal loss over 50 km amounted to approximately 9 dB, representing nearly 87% power loss.

As illustrated in Figure 13, two key observations were made:

1. Backward pumping, where the pump signal propagates opposite to the data signal, provides higher amplification efficiency.
2. The Raman gain factor is heavily polarization dependent, requiring the use of two diodes (Pump diode 1 and Pump diode 2) to produce depolarized light.

Furthermore, it was observed that adequate fiber length is essential for the generation of Raman scattering [72]. As shown in Diagram 14, the saturation strength of the amplified message exhibited a quasi-linear relationship with increasing pump power. The difference in saturation power between the 10 milli watt and 300 milli watt pump conditions was near about 2.5 dB.

Benefits of Raman Amplifiers:

1. Provide huge optical enhancement & large saturation power.
2. Fully compatible with existing standard single-mode (SM) fibers, requiring no major infrastructure changes.
3. Can operate at any wavelength within the telecommunication spectrum.
4. Exhibit a lower noise figure compared to SOAs and EDFAs, resulting in improved signal quality.
5. Support wavelength conversion capabilities.
6. Offer high transmission capacity, suitable for long-haul and high-data-rate systems.

Can be combined with EDFAs to enhance overall system performance and extend amplification reach.

**Disadvantages of Raman Amplifiers:**

1. Require high pump power levels to achieve effective gain.
2. Demonstrate lower efficiency at specific wavelengths when compared to EDFAs operating under the same pump power conditions.

Demand complex gain control mechanisms to maintain stable operation across varying transmission conditions.

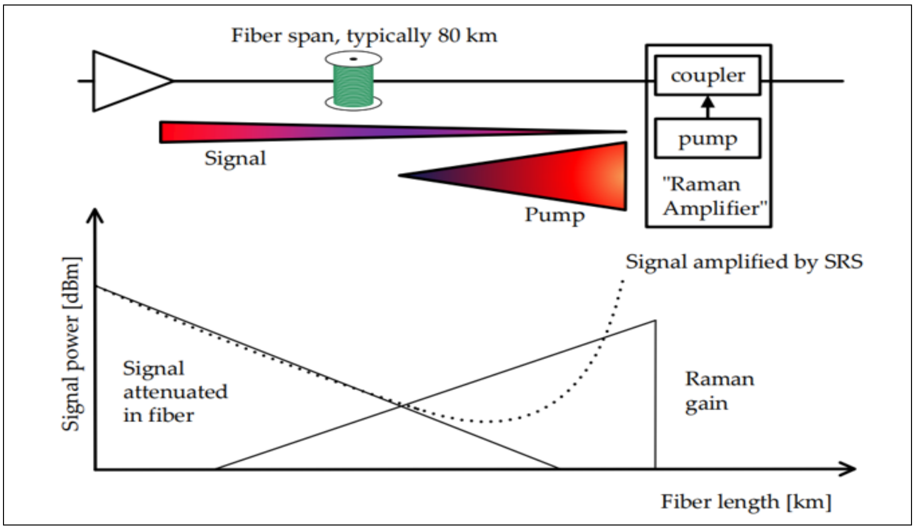


**Fig 12:** Schematic diagram of backward Raman amplification (counterdirectional pumping).

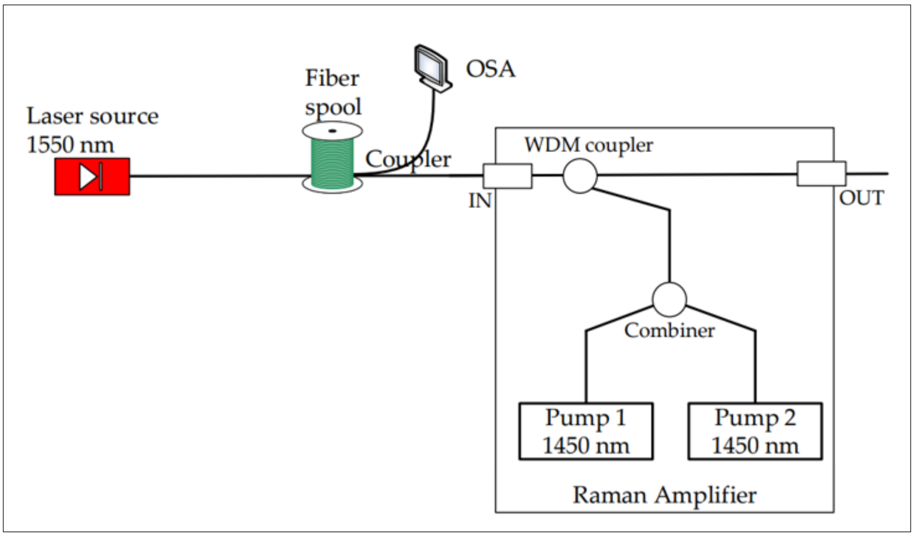


**Fig 13:** Measurement scheme with a Raman amplifier.

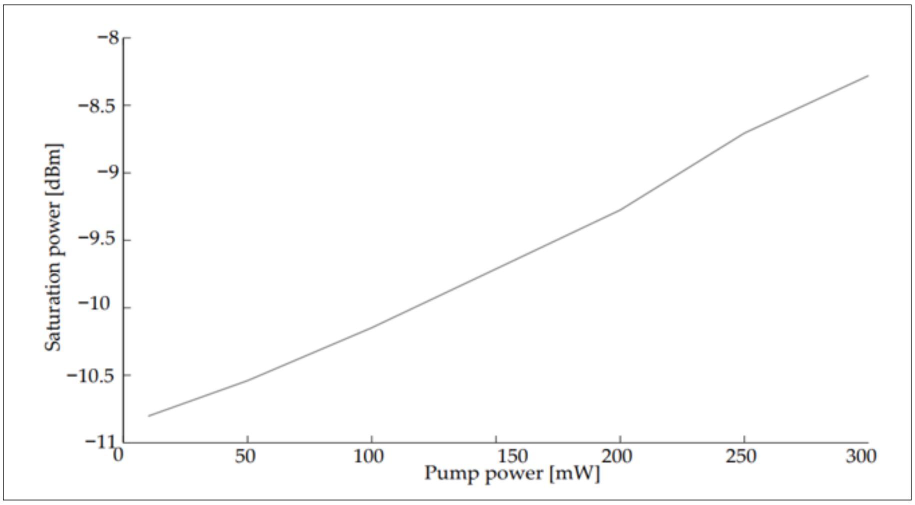


**Fig 14:** Dependence of the saturation power on the pump power.

**Table 1:** Pump power vs. Saturation power of Raman Booster.

| Pump power | Pump wave distance | Amplified wave distance | Amplified saturation power |
|---|---|---|---|
| 10 milli watt | 1455.142 Nano meter | 1552.062 Nano meter | -10.803 dBm |
| 50 milli watt | 1455.162 Nano meter | 1552.060 Nano meter | -10.540 dBm |
| 100 milli watt | 1455.182 Nano meter | 1552.066 Nano meter | -10.148 dBm |
| 150 milli watt | 1455.188 Nano meter | 1552.064 Nano meter | -9.712 dBm |
| 200 milli watt | 1455.184 Nano meter | 1552.064 Nano meter | -9.276 dBm |
| 250 milli watt | 1455.202 Nano meter | 1552.064 Nano meter | -8.706 dBm |
| 300 milli watt | 1455.198 Nano meter | 1552.064 Nano meter | -8.280 dBm |

### a) Brillouin Amplification

The final optical boosting method is Stimulated Brillouin Scattering (SBS). While SBS shares similarities with Stimulated Raman Scattering (SRS), there are key distinctions. SBS occurs only in the backward path and the frequency shift of the scattered light is about 9GHz to 11GHz, in contrast to 13 Tera Hertz (≈100 Nano meter) for SRS. Furthermore, the amplification bandwidth of SBS is much narrower, around 100 MHz, compared to the 30 THz typical of SRS. In SBS, the energy absorbed by the fiber material manifests as acoustic phonons (mechanical vibrations of atoms), unlike the optical phonons produced in SRS.

Brillouin scattering involves a photon to phonon collision, where the annihilation of a pump photon generates a Stokes photon and an acoustic phonon at the same time. These phonons, representing density waves within the fiber, propagate primarily backward with a minor forward component. At a wave distance of 1550 Nano meter, the Stokes frequency shift (9-11 GHz) is about three orders of magnitude smaller than that observed in Raman scattering. This frequency downshift is attributed to the Doppler effect resulting from the motion of acoustic phonons [73].

When the pump and signal waves counter propagate, their frequency difference creates a moving density slop within the fiber. This slope simultaneously scatters pump photons into the message beam, leading to signal amplification. The SBS amplifier is characterized by its extremely narrow bandwidth, typically tens of MHz and inherently includes a narrowband optical filter, allowing for selective signal amplification. Unlike broadband amplifiers such as EDFAs, SOAs or Raman amplifiers, Brillouin amplifiers can achieve very high gain levels, often exceeding 50 dB [74].

However, the narrow gain bandwidth of SBS amplifiers limits their application in conventional data transmission systems. Instead, SBS is increasingly being explored for specialized scientific applications, such as precise time transfer (used in atomic timer synchronization) and ultra-stable frequency shift. These messages operate at low frequencies on the order of hundreds of Mega Hertz for time transfer or continuous wave for periodicity stability and hence possess narrow spectral widths, making them ideal for Brillouin based amplification. In such scenarios, SBS provides highly efficient and stable optical amplification, particularly valuable for ultra-stable periodicity dissemination using restricted linewidth laser devices [75].

**Benefits of Brillouin Repeater:**

1. Provide huge optical amplification and large saturation strength hence making them ideal for restricted band signal amplification.
2. Support wavelength conversion capabilities, allowing flexible signal manipulation.
3. Capable of amplifying extremely weak input signals as low as a few Nano watts by over 50 dB in a one amplification stage.

**Drawback of Brillouin Repeater:**

1. Have a confined application band, primarily suitable for narrowband or specialized systems rather than standard communication networks.
2. They can be affected by nonlinear optical effects, which can introduce signal distortion under certain operating conditions.

**b) Amplifiers for PONs**

High range optical access technology represents a key innovation for next generation users. It offers the ability to deliver high-speed broadband availability to maximum users across access and metropolitan areas while significantly reducing both capital and operational costs for service providers. Most types of photonic repeaters discussed are used in PONs excluding Brillouin repeaters, which are unsuitable because of their narrow amplification bandwidth. Current research is exploring PON architectures capable of extending transmission distances up to 100 km and achieving data rates of around 10 Gb/s. However, such systems are still in the experimental stage and have yet to reach commercial availability.

**Table 2.** Comparison of amplifiers.

| Property | EDFA | RAMAN | SOA |
|---|---|---|---|
| Gain [dB] | Greater than 40 | Greater than 30 | Greater than 30 |
| Wavelength [nm] | 1530-1625 | 1280-1650 | 1280-1650 |
| Bandwidth (3 dB) [nm] | 30-60 | up to 100 | 60 |
| Max. Saturation [dBm] | 30 | 0.75 × pump power | 18 |
| Polarization Sensitivity | No | No | Yes |
| Noise Figure [dB] | Greater than 3.5 | 5 | 8 |
| Pump power | 25 dBm | Greater than 30 dBm | Smaller than 400 dBm |
| Time constant [s] | $1.00\times10^{-1}$ | $1.00\times10^{-14}$ | $2.00\times10^{-9}$ |
| Size | Rack-mounted | Bulk module | Compact |
| Switchable | No | No | Yes |
| Cost factor | Medium | High | Low |

A standard Passive Optical Network (PON) typically supports transmission distances of up to 20 kilo meters with split ratio of 1:64. For instance, the Gigabit Passive Optical Network standard specifies an optical power budget of around 28 dB, enabling downstream rates of 2.488 Giga bits per sec and upstream rates of 1.244 Giga bits per sec. This configuration forms the foundation of most current PON deployments. In long distance communication systems optical repeaters are frequently used to increase transmission distances to hundreds or even thousands of kilometers. Given their relatively low cost, optical amplifiers are considered practical for integration into PONs, where the expense can be distributed among multiple subscribers.

The GPON protocol also allows for a logical reach of up to 60 kilo meters and a split ratio of 1:128 through the optical amplification. Because optical amplifiers maintain signal transparency, they are well-suited for both GPON and Gigabit Ethernet PON (GEPON) technologies. These amplifiers serve as a vital component of next-generation access (NGA) PON systems. Extended-reach PONs provide several key benefits: they allow customers located far from the central office (CO) to connect efficiently, ensure effective resource sharing in sparsely populated regions and enable network consolidation by reducing the number of head-end nodes that operators need to manage [76].

There are four main categories of photonic repeaters applicable to PONs:

i) $Er^{+}$ ions doped fiber amplifiers.
ii) Thulium-doped repeaters for 1490 nm downstream signals and Praseodymium-doped amplifiers for 1310 nm upstream signals.
iii) Semiconductor optical amplifiers.
iv) Raman amplifiers.

Among all above, EDFA is widely utilized in metropolitan and long-haul communication networks because they deliver high gain and output power with a favorable noise figure across the 1530-1565 nm wavelength range. Current PON standards incorporate EDFAs mainly for analog video transmission often referred to as overlay PONs.

An alternative option is the SOA, which offers lower gain and higher noise than EDFAs, has the advantage of wavelength flexibility and faster gain dynamics making it suitable for burst mode upstream transmission. Raman amplifiers can also be used for downstream signal enhancement but their application is limited by the high cost and safety concerns associated with the powerful pump lasers required for operation.

Furthermore, Forward Error Correction (FEC) technology plays an essential role in extending PON performance. While FEC is already integrated into GPON and GEPON frameworks, future PON systems may adopt enhanced versions of FEC for improved reliability. Experimental demonstrations have shown that combining optical amplifiers located at intermediate powered sites with FEC can potentially enable 10 Gb/s transmission rates and high split ratios up to 1:1024 in next-generation PON designs [76] [77].

Various Passive Optical Network (PON) architectures use wavelengths of C-band, such as the 1530 nm and 1550 nm channels common in Coarse Wavelength Division Multiplexing (CWDM) systems for connections between the Optical Line Terminal and Optical Network Units. When Erbium-Doped Fiber repeaters are applied as both power boosters & preamplifiers, the network's optical power can be increased by up to 34 dB [31]. EDFAs are especially advantageous for 1550 nm transmission, a range often utilized for delivering video overlay content.

Other demonstrations include combining Semiconductor Optical Amplifiers (SOAs) with Raman amplification, where speeds of up to 2.5 Gb/s have been achieved using Raman pumps at 1270 nm with powers as high as 1 W. While effective for increasing reach in rural settings, the high pump power required is categorized as Class IV, presenting significant eye safety concerns.

Major field trials, such as those by British Telecom have showcased long reach PON solutions integrating EDFAs and SOAs, achieving symmetric 10 Giga bits per sec transmission at distances of 100 kilo meters serving up to 1024 users with cost effective ONU transceivers [79]. Another large-scale deployment, known as SuperPON, reached a span of 100 km and served 2048 ONUs with architecture including feeder and add-drop fiber sections. EDFAs and SOAs played vital roles in this setup.

Further research from the Optical System Group at University of Cork demonstrated WDM-TDM LR-PON networks supporting multiple wavelength pairs, each covering 100 km and supporting 1:256 split ratios per segment amounting up to 4352 users for 17 PON segments [80]. Another collaborative project, PIEMAN extended the reach to 100 km using 32 dense WDM channels, each operating at 10 Gb/s and 1:512 splits, theoretically supporting over 16,000 users.

**Table 3:** Long-reach passive optical network (LR-PON) projects [84-92].

| Name of project | Standard used | Distance covered [km] | Operating wavelength | Down / upstream data rate [GB/S] | Number of end users |
|---|---|---|---|---|---|
| Acts-planet | APON | 100 | 1 | 2.5/0.311 | 2048 |
| British telecom | GPON | 135 | 40 | 2.5/1.25 | 2560 |
| Wdm-tdm | | 100 | 17 | 10/10 | 4352 |
| Pieman | | 100 | 32 | 10/10 | 16384 |
| We-pon | GPON/EPON | 100 | 16 | 2.5/2.5 | 512 |
| Sardana | GPON/EPON | 100 | 32 | 10/2.5 | 1024 |

Researchers are also exploring Extended reach ring & spur network architectures PONs, where every PON section connects to a central ring, enabling bi-directional transmission and improving fault tolerance. The WE-PON system developed in Korea utilizes such a ring and spur approach and supports 512 users via multiple wavelengths added and dropped at remote nodes equipped with amplifiers and optical add-drop multiplexers. A different ring-based architecture, SARDANA, transmits 32 wavelengths around a ring with each supporting 32 end-users and utilizes reconfigurable SOA based ONU units to serve more than 1000 customers. Comparisons of these various long-reach PON projects and their capabilities are provided in Table [3].

Numerous experimental evaluations of various optical amplifiers within Passive Optical Networks (PONs) have been undertaken. Overall findings indicate that Brillouin amplifiers are unsuitable for such applications due to their inherent physical limitations [93]. $Er^+$ ion Doped Fiber Amplifiers are majorly applied in analog radio frequency, overlay video services and Wavelength Division Multiplexing PONs (WDM-PONs), particularly operating within the C & L band wavelength regions [102]. Some other fiber amplifier variants, such as Thulium doped amplifiers for downside transmission and Praseodymium doped amplifiers for upside transmission are also viable for PON integration [108].

Although Raman amplifiers can be utilized in PONs, their practicality is limited by the high cost and the safety risks associated with the powerful optical pumps required for downstream amplification [115]. Among all discussed options, Semiconductor Optical Amplifiers (SOAs) are regarded as strong candidates for future generations of long-reach PONs. Their compact size, cost efficiency and adequate gain performance make them promising components for next-generation network designs [21].

**Conclusion**

This paper centers on extending the coverage of Passive Optical Networks, addressing their usage in both active and passive optical systems. Extending transmission distances without the use of amplifiers or boosters is not achievable, so this discussion covers the fundamental concepts about signal reoccurrence and boosting along with detailed explanations of optical fiber amplifiers. The history, operational principles and fundamental configurations of various amplifier types are thoroughly reviewed.

Although numerous standards exist for high-speed PONs and new standards are in development, emerging trends such as the deployment of EDFAs, Raman amplifiers and SOA amplifiers in PONs remain under documented. Experimental measurements illustrate that Raman amplifiers can effectively boost signals even with relatively low pump powers (~300 mW). This article not only explains amplification basics but also reviews current research on applying optical fiber amplifiers in PON networks, presenting both straightforward and complex signal regeneration solutions.

Moreover, the paper highlights the importance of open networking trends promoted by large data center operators, which aim to reduce vendor lock-in and promote technological flexibility in PON deployments. Although many open networking practices are not yet standardized, they are gaining traction worldwide, mainly in Asian & North American continent. With optical amplification, future PONs might support novel applications like precise time shift and scattered fiber sensing, while they can be become meaningful with evolving user demands and open network architectures.

**Abbreviations**

The abbreviations that are used in this manuscript are described below:

ALS: Automatic laser shutdown
APC: Angled physical contact
ASE: Amplified spontaneous emission
CESNET: Czech Education and Scientific Network
CD: Chromatic dispersion
CO: Central office
CW: Continuous wave
CWD: Coarse wavelength division multiplexing
DCF: Dispersion compensating fiber
DRA: Distributed Raman amplifier
DRS: Distributed Rayleigh scattering
DSP: Digital signal processing
DWDM: Dense wavelength division multiplexing
GE: Gigabit Ethernet
GEPON: Gigabit Ethernet passive optical network
GPON: Gigabit passive optical network
GVP: Group velocity dispersion
IEEE: Institute of Electrical and Electronics Engineers
ITU: International Telecommunication Union
LAN: Local area network
LRA: Lumped Raman amplifier
MFD: Mode field diameter
NF: Noise figure
NGA: Next-generation access
NICs: Network interface controllers
OADM: Optical add-drop multiplexer
ODN: Optical distribution network
OEO: Optical to electrical to optical
OLT: Optical line terminal
ONU: Optical network unit
OOO: All-optical
OSNR: Optical signal to noise ratio
P2MP: Point to multipoint
PDFFAs: Praseodymium doped fluoride fiber amplifiers
PIEMAN: Photonic integrated extended metro & access network
PMD: Polarization mode dispersion
RE-PON: Reach extended passive optical network
RF: Radio frequency
RN: Remote area node
RSOA: Reconfigurable semiconductor optical amplifier
SARDANA: Scalable advanced ring dense access network architecture
SNR: Signal to noise ratio
TW: Traveling wave
WDM: Wavelength division multiplexing
WDM-TDM LR-PON: Wavelength and time-division multiplexing long-reach passive optical network WWW World Wide Web

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