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Application of Amplifying Technologies to Increase Optical Signal Power

Abstract

In modern times, due to the rapid development of information and communication technologies, the demand for broadband and high-speed data transmission systems is constantly increasing. One of the most reliable and effective solutions to meet these needs is the application of optical fiber communication systems. Signal transmission via optical fibers is considered one of the most modern technologies in terms of high bandwidth, low attenuation and resistance to electromagnetic influences.

However, as the distance increases, optical signals weaken, which limits the quality and range of transmission. In order to prevent such signal weakening and maintain quality during long-distance transmission, various optical amplification technologies are applied. These technologies allow the signal to be amplified directly in optical form without converting it into electrical form, thereby increasing the overall efficiency of the system.

The main purpose of this article is to examine the types of amplification technologies used to increase the power of an optical signal, their working principle and application areas. In particular, the advantages and limitations of advanced technologies such as EDFA (Erbium Doped Fiber Amplifier), RAMAN amplifiers, and SOA (Semiconductor Optical Amplifier) will be analyzed.

Keywords: *optical signal power, optical amplifier, EDFA (Erbium Doped Fiber Amplifier), RAMAN amplifiers, SOA (Semiconductor Optical Amplifier)*

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Optik siqnal gücünün artırılması üçün gücləndirici texnologiyaların tətbiqi

Xülasə

Müasir dövrdə informasiya-kommunikasiya texnologiyalarının sürətli inkişafı ilə əlaqədar olaraq, genişzolaqlı və yüksək sürətli məlumat ötürmə sistemlərinə olan tələbat durmadan artır. Bu ehtiyacları qarşılamaq üçün ən etibarlı və effektiv həll yollarından biri optik lifli kommunikasiya sistemlərinin tətbiqidir. Optik liflər vasitəsilə siqnal ötürülməsi, yüksək bant genişliyi, aşağı zəifləmə və elektromaqnit təsirlərinə qarşı davamlılıq baxımından ən müasir texnologiyalardan sayılır.

Lakin, məsafə artdıqca optik siqnalların zəifləməsi müşahidə olunur ki, bu da ötürmənin keyfiyyətini və məsafəsini məhdudlaşdırır. Siqnalın belə zəifləməsinin qarşısını almaq və uzun məsafəli ötürmə zamanı keyfiyyətin qorunub saxlanması üçün müxtəlif **optik gücləndirici texnologiyalar** tətbiq olunur. Bu texnologiyalar siqnalın elektrik formasına çevrilmədən, birbaşa optik formada gücləndirilməsinə imkan verir və bununla da sistemin ümumi məhsuldarlığını artırır.

Bu məqalədə əsas məqsəd, optik siqnal gücünün artırılması üçün istifadə olunan gücləndirici texnologiyaların növlərini, onların iş prinsipini və tətbiq sahələrini araşdırmaqdan ibarətdir. Xüsusilə EDFA (Erbium qatqılı lif gücləndiriciləri), RAMAN gücləndiriciləri, və SOA (yarımkeçirici optik gücləndiricilər) kimi qabaqcıl texnologiyaların üstünlükləri və məhdudiyyətləri təhlil ediləcəkdir.

Açar sözlər: optik siqnal gücü, optik gücləndirici, EDFA (Erbium Doped Fiber Amplifier), RAMAN gücləndiriciləri, SOA (Semiconductor Optical Amplifier)

Introduction

In the 21st century, where the information society is rapidly developing, the need for high-speed, reliable and broadband data transmission technologies is increasing day by day. Optical fiber communication systems play a key role in meeting these requirements. Signal transmission via optical fibers is considered one of the most effective technologies in terms of resistance to electromagnetic interference, low energy losses and high throughput.

However, increasing distance leads to signal attenuation and quality degradation. For this reason, the problem of optical signal amplification is one of the important technological challenges facing modern communication systems. It is for this reason that the development and proper application of optical amplifier technologies remains relevant in this field.

Research

In particular, the expansion of 5G technology, the increase in data centers and the development of cloud-based services necessitate further improvement of optical communication systems and amplifiers that are part of them. In this regard, the study and application of amplifier technologies aimed at increasing optical signal power is considered one of the important and urgent scientific and technical issues of the modern era.

Main part

Optical fiber-based communication systems are considered the most suitable technology for high-speed and broadband data transmission in modern times. The optical signal transmitted in these systems weakens over time for various reasons: absorption, scattering and dispersion in the fiber are the main factors of this weakening. In order to maintain the quality of the weakening signal and ensure its effective transmission over long distances, the application of optical amplification technologies is important. Optical amplifiers provide amplification of the transmitted signal directly in the optical medium without converting it into an electric field. This allows for the simplification of optical systems, signal recovery without delay and increased overall efficiency (Agrawal, 2012). The most widespread optical amplification technologies are Erbium-Doped Fiber Amplifiers (EDFA), Raman Amplifiers and Semiconductor Optical Amplifiers (SOA). Each technology is distinguished by its uniqueness and advantages, but also has certain limitations.

Erbium-Doped Fiber Amplifiers (EDFA)

One of the main technologies used in the process of signal amplification and long-distance transmission in optical communication systems is Erbium-Doped Fiber Amplifiers (EDFA). These amplifiers were developed in the late 1980s and quickly became the main signal amplification tool in modern optical networks. Their advantage is that they allow the signal to be amplified entirely in an optical medium, without converting it into an electrical signal. This feature makes EDFA an ideal solution in terms of both transmission speed and energy efficiency (Chraplyvy, 2015).

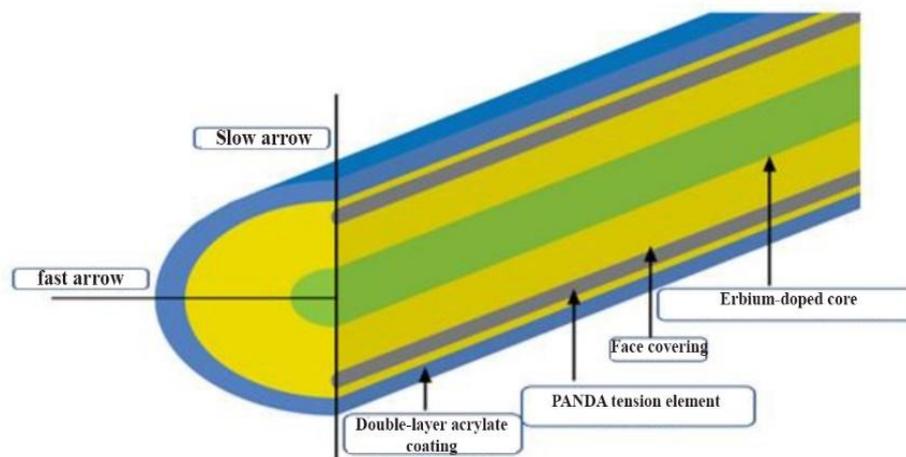


Figure 1. Cross-section of an erbium-doped polarization-maintaining core-pumped fiber

The basic working principle of an EDFA is based on stimulated emission. In this process, the signal is amplified by absorbing the energy of ions that have been previously raised to a high energy level by a pump laser as it passes through an optical fiber doped with erbium ions. The pump lasers used in an EDFA system typically operate at a wavelength of 980 nm or 1480 nm. These wavelengths are considered optimal for exciting erbium ions to their energy levels. The excited Er^{3+} ions as a result of the pumping process produce a copy of that photon by stimulated emission under the influence of the signal photon, resulting in an increase in signal intensity.

A typical EDFA system consists of the following components: an erbium-doped optical fiber (active medium), a pump laser source, a WDM (wavelength multiplexer), optical isolators, and signal monitoring systems. WDM allows the signal and pump beams to be directed onto the same fiber, while isolators prevent signal return and noise. The output signal strength and quality are monitored by signal monitoring systems (Ellis, Suibhne, 2008).

The main advantages of EDFA amplifiers are: high gain (20–30 dB or more), low noise figure (3–5 dB), wide optical bandwidth (especially C-band and L-band), high reliability, passive operation, and full compatibility with fiber-optic systems. These features make EDFAs particularly indispensable in long-haul optical communication systems, networks using WDM technology, and transatlantic cable systems.

However, EDFAs also have some limitations. They are mainly related to the limited operating spectrum (mainly C-band and L-band only), limited dynamic range, and the need for high pump power. In addition, the integration of EDFA amplifiers into microoptical or integrated systems can pose certain technical challenges. For this reason, alternative amplifier technologies, such as Raman amplifiers and semiconductor optical amplifiers (SOA), have also been investigated in recent years.

The application areas of EDFA are diverse. This technology is widely used in telecommunications systems, metro networks, broadband internet provision, optical sensor systems, as well as military communications. EDFA plays an important technological role in every field where signal transmission over long distances with high quality and minimal loss is required.

Future research on the development of EDFA technologies is related to the creation of amplifiers operating in a wider spectral range, more efficient use of pump energy, improved thermal management, and integration into chip-based miniature systems. In addition, the application of artificial intelligence and machine learning-based control systems may also enable real-time optimization, automatic adjustment, and fault prediction of EDFAs (Kaminow, Li, Willner, 2013).

Thus, Erbium-Doped Fiber Amplifiers act as one of the most widespread and technologically advanced means for effective and reliable signal amplification of modern optical communication systems. Its use allows fiber-optic networks to have more stable, fast and long-distance communication capabilities.

Raman Amplifiers.

Raman amplifiers are one of the innovative amplifier technologies based on nonlinear optical effects used to amplify optical signals. This type of amplifier got its name from the Raman scattering effect discovered by the Indian physicist C.V. Raman in 1928. Raman amplifiers operate on the basis of the stimulated Raman scattering phenomenon occurring in optical fibers and use the fiber itself as the active medium. This distinguishes them from classical erbium-doped fiber amplifiers (EDFA) and gives them a number of important advantages (Kato, et al., 2021).

The Raman amplification process is carried out by using an additional powerful pump laser in the optical fiber through which the signal is transmitted. This pump has a wavelength shorter (i.e. higher frequency) than the signal wavelength. As the pump signal travels along the optical fiber, it transfers its energy to the signal wave through stimulated Raman scattering, resulting in an increase in signal power. Since the amplification occurs in the fiber through which the signal travels, Raman amplifiers are also called distributed amplification systems.

Raman amplifiers are implemented in two main ways: co-pumped and counter-pumped. In the co-pumped scheme, the pump signal and the signal travel in the same direction, while in the counter-pumped scheme, the pump signal is sent in the opposite direction to the signal. Both approaches have their advantages. Co-pumped amplification starts amplification at the beginning of the signal, which reduces the initial decay of the signal. Counter-pumped amplification can provide a more stable gain profile and reduce the signal-to-noise ratio (Keiser, 2010).

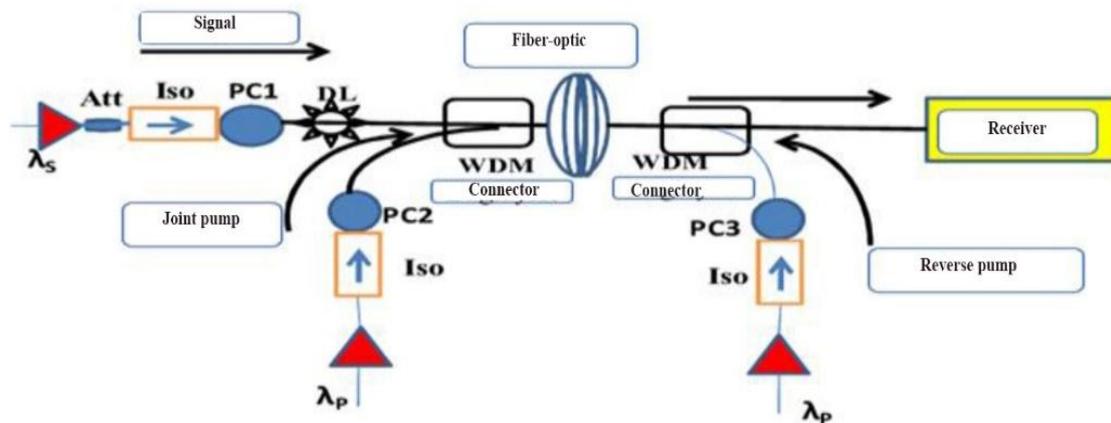


Figure 2 Schematic of a Raman Amplifier

One of the important advantages of Raman amplifiers is their wide spectral flexibility. Since the Raman scattering process can occur at any wavelength, this amplifier technology is not limited to C-band or L-band. This makes it more flexible and suitable for different wavelengths compared to EDFA. In addition, Raman amplifiers are distinguished by their low noise figure. This is especially important in systems that require high-quality transmission of weak signals.

However, Raman amplifiers also have some technical difficulties and limitations. The biggest difficulty of this technology is the need for high-power pump lasers. Such lasers are more complex and expensive to manufacture and control. At the same time, Raman amplifiers have a lower gain compared to EDFA, and the amplification efficiency is very sensitive to the length of the fiber and the parameters of the signal. Another limitation is the increased likelihood of nonlinear effects in the fiber - for example, four-wave mixing and cross-phase modulation. This can have a negative impact on signal quality (Kumar, et al., 2017).

Despite all these features, Raman amplifiers play an important role in modern optical communication systems. When used in conjunction with EDFAs – that is, in hybrid amplifier systems – they allow for optimization of signal amplification. Such hybrid systems are ideal for environments requiring both broadband and low noise. For example, the Raman amplifier amplifies the signal at the beginning and middle of the fiber, while the EDFA performs an additional amplification function at the output.

Raman amplifiers are mainly used in the following areas: ultra-long-haul optical networks, high-capacity WDM systems, submarine communication lines, as well as in research and scientific and technological systems. Especially in recent years, interest in Raman amplifiers has been growing in high-speed transmission technologies such as 400G and 800G.

The development of Raman amplifier technologies in the future is directly related to the creation of more compact and energy-efficient pump sources, the management of nonlinear effects, and the application of artificial intelligence-based control mechanisms. Research is being conducted in all these areas, and it is expected that Raman amplifiers will have wider application areas as a result.

Semiconductor Optical Amplifiers (SOA)

One of the modern technologies used for optical signal amplification is the semiconductor optical amplifier (SOA). This type of amplifier is similar to laser diodes in terms of structure and operating principle, but their main difference is that their purpose is to amplify the signal through stimulated emission in an active medium. SOAs are powered by an electric current and allow the signal to be amplified directly optically without the need for optical-electrical-optical conversion. This makes them suitable for use in various fields – especially in integrated optical systems and compact devices (Liu, et al., 2020).

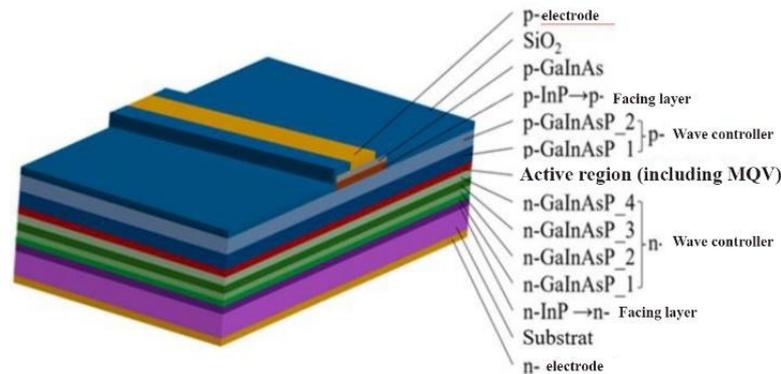


Figure 3 Epitaxial structure of a designed semiconductor optical amplifier (SOA)

The working principle of SOA is as follows: when the active semiconductor region is excited by an external electric current, electrons in it rise to a high energy level. When a signal photon passes through this region, a stimulated emission process occurs, resulting in the creation of a new photon - which leads to signal amplification. Thus, SOA both increases the signal power and acts as a passive optical amplifier (Ramaswami, Sivarajan, Sasaki, 2009).

The structure of SOAs usually consists of three main parts: an active semiconductor layer (usually InGaAsP or AlGaAs-based), input and output optical fiber interfaces, and a power supply consisting of contact electrodes. In some cases, multiple quantum well (MQW) structures are also used for higher power and lower noise. Such structures play an important role in increasing the optical gain effect and reducing nonlinear effects.

The most important advantages of SOA are as follows (Senior, Jamro, 2009):

- Compact size and integration: SOAs can be easily integrated into integrated optical circuits and chip-based systems due to their small size.
- Low power consumption and electrical control: Since they operate with an external power source, they are more flexible in operation and use.
- Wide operating range: SOAs can operate at different wavelengths, which makes them suitable for flexible systems.
- Multifunctional use: SOAs can be used not only as amplifiers, but also as optical switches, modulators, and wavelength converters.

However, SOAs also have some limitations. The most important problem is the relatively high noise figure. Since spontaneous emission also occurs in addition to stimulated emission, the output signal carries additional noise. This can reduce the quality of the signal to some extent. In addition, nonlinearities and effects – such as cross-gain saturation, four-wave mixing (FWM) and wavelength-dependent amplification – can cause signal distortion. For this reason, SOAs are commonly used in short-haul communication systems and optical circuits requiring high integration.

Important application areas for SOAs are (Xu, et al., 2016):

- Signal amplification and routing in PON (passive optical networks) and FTTH (fiber-to-the-home) systems;
- Use as optical switches in optical switching and switching systems;
- Optical network control elements for wavelength conversion and regeneration;
- In laboratory and research areas, in the study of nonlinear optical effects and in the manipulation of optical signals.

In terms of future development prospects, extensive research is being conducted on the application of new materials (for example, wideband semiconductors), noise reduction technologies, and nonlinear effect control mechanisms to improve the performance of SOAs (Zhang, et al., 2022). At the same time, the placement of SOAs as a functional block within photonic integrated circuits

(PIC) indicates that they can also play a promising role in the fields of optical computing and quantum communication.

Conclusion

As a result of the research, it has been determined that the application of optical amplifier technologies is necessary to prevent the attenuation that occurs due to distance during optical signal transmission and to maintain signal quality. These technologies allow the signal to be amplified directly optically without being converted to an electrical form, thereby increasing both the transmission distance and the overall efficiency of the communication system.

The most widely used amplifier technologies — Erbium-doped fiber amplifiers (EDFA), Raman amplifiers, and Semiconductor optical amplifiers (SOA) — are distinguished by their various advantages and application areas. EDFA is distinguished by high-quality signal transmission and low noise level, while Raman amplifiers are distinguished by wide spectrum capabilities. SOA is more compact and suitable for integrated systems.

As a result, the correct selection and application of these amplifier technologies plays an important role in the design and development of communication systems. Further improvement of these technologies in the future will allow expanding the capabilities of optical communication systems and transition to a new qualitative stage in information transmission.

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