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Abstract. This paper comprehensively reviews the fundamental principles of Erbium-Doped Fiber Amplifiers (EDFAs) and their critical advancements in submarine communication systems. EDFAs amplify optical signals through stimulated emission of Er^{3+} ions embedded in a silica matrix, with key research focuses on gain saturation dynamics and amplified spontaneous emission (ASE) noise suppression. Among noise detection methods, the shot-noise-limited input reference signal is widely adopted due to its compatibility with existing photonic hardware, while quantum-compressed light (relying on phase-sensitive amplification) and known noise injection techniques face limitations from coherence degradation and secondary noise amplification risks. In submarine communication, fiber optic cables have displaced satellite systems as the primary backbone for intercontinental data transmission, owing to their 30-fold lower latency (≈30 ms per 8,000 km), terabit-level bandwidth, and immunity to electromagnetic interference. However, complex marine environments—such as deep-sea pressures exceeding 100 MPa and chromatic dispersion effects—demand optimized EDFA configurations with adaptive gain control and hybrid wavelength-division multiplexing (WDM) architectures. Dense WDM (DWDM) enhances capacity via 80+ wavelength channels in parallel transmission, yet requires advanced nonlinear effect mitigation (e.g., four-wave mixing suppression) and dispersion compensation modules. Future advancements hinge on dynamic tunable optical amplifiers with real-time feedback loops, enabling adaptive power allocation and quantum noise suppression to transcend current transmission limits in extreme underwater conditions.

INTRODUCTION

Long-distance optical communication technology has experienced rapid development since the 1980s. Early systems relied on optoelectronic repeaters for signal regeneration, which were limited by their inability to handle multiple wavelength channels.

The commercialization of EDFAs in the 1990s revolutionized the field by enabling all-optical amplification. A single EDFA module can amplify over 40 wavelength channels simultaneously, increasing system capacity by two orders of magnitude. Notably, EDFAs reduce noise figures by 8–10 dB compared to traditional methods, extending unregenerated transmission distances to 500 km. This breakthrough has driven the global deployment of submarine fiber optic systems, which now carry 99% of international data traffic [1].

This paper focuses on the key technology evolution of erbium-doped fiber amplifiers in modern optical transmission systems. System discussion: The principle and mechanism of erbium-doped fiber amplifier; Common schemes for noise detection; Development of erbium-doped fiber amplifier technology in deep-sea high-pressure environment; Pay attention to the optimization measures of dense wavelength division multiplexing system.

This paper focuses on the technological evolution of erbium-doped fiber amplifier and its application in submarine communication:

The basic principle and characteristics of EDFA: the stimulated emission mechanism of erbium ion is analyzed, and the gain saturation and noise characteristics are discussed.

Optical amplification noise detection methods: compare the advantages and disadvantages of shot noise basis, compressed light and other technologies and applicable scenarios;

The influence of seabed environment on communication system: analysis of challenges such as deep sea pressure and dispersion effect, compression encapsulation and dynamic compensation strategies;

Optimization path of dense wavelength division multiplexing (DWDM) : nonlinear effect suppression and dynamic modulation amplification techniques are discussed.

Conclusions and Prospects: The role of EDFA in promoting the global submarine cable network is summarized, and future directions such as quantum noise suppression are proposed.

PRINCIPLES AND CHARACTERISTICS OF EDFAS

Principles

EDFAs amplify signals via stimulated emission of Er^{3+} ions in a silica matrix. Pump light excites Er^{3+} ions from the ground state ($^4I_{15/2}$) to an excited state, followed by non-radiative relaxation to a metastable state ($^4I_{13/2}$). Signal photons trigger stimulated emission, releasing coherent photons that amplify the signal. Efficiency depends on optimizing erbium ion concentration and fiber geometry to maximize pump energy conversion [2].

Key Characteristics

Gain saturation is a nonlinear phenomenon in EDFAs where the optical gain decreases significantly when the input signal power exceeds a critical threshold (typically 10–15 dBm). This occurs due to the depletion of metastable Er^{3+} ions in the silica matrix, which limits the population inversion required for stimulated emission. To mitigate this effect, adaptive gain control algorithms and distributed pumping schemes are implemented, enabling dynamic adjustment of pump power to maintain stable amplification across varying input conditions [3].

Amplified Spontaneous Emission (ASE)Noise originates from spontaneous radiative transitions of metastable Er^{3+} ions, generating broadband noise across the 1530–1565 nm spectrum. This noise is amplified alongside the signal in cascaded EDFA stages, progressively degrading the signal-to-noise ratio (SNR) in long-haul submarine links. Current countermeasures include optical filtering with tunable Bragg gratings and hybrid amplification architectures combining Raman and EDFA technologies to suppress ASE accumulation [4].

NOISE DETECTION METHODS IN OPTICAL AMPLIFICATION

Reference Signal Selection

The shot-noise-limited input method establishes a reference baseline by attenuating signals to quantum noise-dominated levels. This approach leverages the Poissonian statistics of photon detection, providing a practical framework for characterizing amplifier noise figures without requiring complex quantum-state preparation. Its widespread adoption stems from compatibility with standard optical spectrum analyzers and real-time monitoring systems in field-deployed submarine repeaters [5].

Quantum-compressed light utilizes phase-sensitive amplification to reduce noise below the shot-noise limit, theoretically achieving 3–10 dB noise suppression. However, its implementation in fiber-optic systems faces challenges from polarization mode dispersion and nonlinear phase shifts, which degrade squeezing coherence over multi-kilometer spans. Recent advancements in dispersion-engineered fibers and phase-stabilized pumps aim to enhance transmission fidelity for subsea applications [6].

This technique injects calibrated noise signals to characterize amplifier responses under controlled conditions. While effective for laboratory calibration, secondary amplification of injected noise components can artificially inflate measured noise figures, complicating system-level performance evaluations. To address this, differential measurement protocols and frequency-domain noise cancellation algorithms have been developed to isolate intrinsic amplifier noise [7].

Noise Measurement Techniques

Optical Methods Optical noise analysis employs spectral decomposition of ASE using high-resolution monochromators or tunable lasers. By measuring the amplified noise power spectral density (PSD) across the C-band, these methods enable precise calculation of noise coefficients and gain tilt profiles. Integration with wavelength-selective switches further allows dynamic noise suppression in reconfigurable DWDM networks [8].

Optoelectronic/Electrical Methods These techniques convert optical intensity fluctuations into electrical signals via high-speed photodetectors, followed by noise power quantification using RF spectrum analyzers. They excel in characterizing relative intensity noise (RIN) and intermodulation distortions in multi-channel systems. Recent implementations incorporate machine learning classifiers to differentiate between ASE noise and nonlinear impairments in real-time monitoring scenarios.

IMPACT OF SUBMARINE ENVIRONMENTS ON FIBER OPTIC SYSTEMS

With its high capacity characteristics, submarine cables are ideal for carrying the rapidly growing broadband communications and applications such as Internet, data and voice. Contemporary optical fiber technology supports the concurrent transmission of millions of voice channels, with its data-carrying capacity undergoing exponential growth cycles, projected to persist in the foreseeable future.

In contrast to geostationary satellites, satellite communications signals travel about 72,000 kilometers round trip, resulting in a significant delay of at least a quarter of a second, while signals transmitted over 8,000 kilometers by submarine cables have a delay of about one-thirtieth of a second, which is almost imperceptible in conversation. The sound quality of fiber optic cable transmission is extremely clear and independent of atmospheric conditions, while providing excellent confidentiality and reliability. Third-generation fiber-optic architectures achieve single-channel throughputs of 5 Gb/s per fiber pair (operating near 1.55 μm wavelengths), with effective optical bandwidths spanning 250–300 GHz, which is limited by the self-filtering effect of cascades of erbium-doped fiber amplifiers (EDFA).

Recent advancements have driven the deployment of next-generation systems. As pioneers of fourth-generation undersea fiber networks, these implementations enhance signal integrity through advanced optical amplification [9]. By integrating erbium-doped fiber amplifiers (EDFAs) with dense wavelength-division multiplexing (DWDM), they achieve multi-channel throughput scaling. Concurrently, escalating demands for voice and data transmission propel continuous expansion of transoceanic cable capacities, with an annual growth rate of about 25% in both the Atlantic and Pacific regions. The need for higher submarine cables has led to an increase in coaxial cable diameters, but cable diameters are limited from an economic and mechanical point of view. Water depth, link order and dispersion coefficient have significant effects on the performance of submarine fiber optic cable system, especially in the condition of high water depth, it is necessary to optimize the system parameters to maintain the transmission quality.

OPTIMIZATION STRATEGIES FOR DWDM SYSTEMS

Advancements in photonic technologies spanning component design, network architecture, and system integration have addressed escalating requirements driven by bandwidth-intensive services [10]. Current 40-channel optical frameworks operating at 10 Gb/s per channel struggle to fulfill the escalating demands of modern high-throughput networks. Emerging solutions now enable multi-terabit transmission over extended spans, supporting per-channel data rates from 40 Gb/s to 100 Gb/s. Due to high-speed online services and broadband applications (such as ultra HD TV, video conferencing, etc.), data transmission is expected to increase further in the future. This trend is driving the development of broadband communications infrastructure towards greater speeds and longer transmissions for higher end users.

Dense wavelength division multiplexing (DWDM) architectures employ wavelength-division multiplexing (WDM) principles to enable multi-channel signal transmission over a single optical fiber, with each channel operating at unique wavelengths. Recognized for their scalability and efficiency, DWDM frameworks have been formally adopted by global telecommunications standards bodies as foundational elements of core network infrastructure. Typical DWDM systems and networks cover the entire network space, including intra-building networks, networks, cities, long-distance and ultra-distance networks. These coverage ranges from meters across home networks to hundreds or even thousands across fiber optic cables. However, the transmission speed of optical communication systems will reach 40-100 Gb/s. The exponential growth in multimedia traffic necessitates adaptive enhancements in DWDM architectures to maintain service quality. To fully leverage the capabilities of wavelength-division multiplexing (WDM) networks, comprehensive analysis of the transmission medium's physical properties—including chromatic dispersion and nonlinear Kerr effects—is critical for system-wide optimization [7]. These phenomena predominantly degrade signal integrity in multi-channel high-speed transmissions, where concurrent propagation of optical carriers amplifies waveform distortions. Mitigating such impairments remains a key objective, aiming to maximize spectral efficiency while minimizing signal deterioration.

Contemporary optical amplification technologies offer enhanced efficiency and cost-performance ratios, delivering consistent power amplification independent of input signal properties. These devices typically utilize laser-driven stimulated emission mechanisms to achieve signal enhancement. A critical performance metric for such systems is the gain coefficient, directly proportional to the optical pumping power applied to the active medium.

Standard Erbium-doped fiber amplifiers (EDFAs) exhibit gain coefficients ranging from 20 to 30 dB with erbium-doped fiber (EDF) lengths of approximately 10 meters. The amplifier's maximum output power is constrained by three primary factors: pump laser intensity, fiber material properties, and EDF length. Configurations employing continuous-wave (CW) lasers operating at 1550 nm for optical pumping allow EDF extensions up to 30 meters, where the pump emission is multiplexed with data signals through wavelength-division multiplexing (WDM) couplers. Key to EDFA performance optimization is the selection of pumping sources; practical implementations predominantly utilize 1550 nm wavelength lasers in co-propagating pumping schemes, ensuring pump photons align directionally with the transmitted signal to maximize energy transfer efficiency.

CONCLUSION

Erbium-Doped Fiber Amplifiers (EDFAs) are indispensable in submarine communication due to their broad gain bandwidth and compatibility with DWDM, enabling multi-terabit transoceanic transmission. However, amplified spontaneous emission (ASE) noise accumulation, gain saturation under high input power, and dynamic control challenges in extreme marine environments (e.g., 100 MPa pressure, temperature fluctuations) limit system scalability. To address these issues, future research should focus on: (1) Quantum noise suppression via phase-sensitive amplification to reduce ASE noise floors; (2) Intelligent optical networks integrating machine learning for real-time gain optimization and nonlinear distortion compensation; (3) Multi-physics simulations combining photonic, mechanical, and thermal models to design pressure-tolerant EDFA modules. These advancements will enhance the reliability of submarine cables and support petabit-scale transmission demands driven by global data growth.

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