Optimization Scheme Design of Raman Fiber Amplifier

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Abstract. The ongoing advancement and progression within the domain of optical fiber communication fundamentally relies upon the persistent refinement and continuous enhancement of large-scale performance characteristics and capabilities. Within this critical technological landscape, Raman fiber amplifiers constitute a vital component and play an indispensable role in the process of signal transmission across extensive networks. This importance stems primarily from their inherent capacity and unique ability to more effectively satisfy and better accommodate the stringent requirements and growing demands associated with contemporary high-speed, large-capacity optical communication infrastructures and systems. This paper offers a concise introduction and outlines the fundamental working principle underlying the operation of Raman fiber amplifiers. Furthermore, it presents and describes several distinct algorithmic optimization design schemes specifically conceived and developed to address two significant existing limitations: the high cost factor and the constrained system efficiency currently encountered. These presented design schemes encompass a cascaded and enhanced Raman fiber amplifier design utilizing the Wild Horse optimization algorithm, an alternative design approach integrating neural network methodologies synergistically with the artificial bee colony algorithm, a design strategy for second-order Raman fiber amplifiers incorporating Convolutional Neural Network-Long Short-Term Memory (CNN-LSTM) techniques, and finally, an optimization scheme tailored for long-distance optical transmission systems fundamentally based on the implementation of distributed Raman fiber amplifier technology. The paper additionally undertakes a comparison, systematically evaluating the respective advantages and disadvantages inherent in these optimized design methodologies.

INTRODUCTION

As the core technology of modern information transmission, the development of optical fiber communication relies heavily on the continuous optimization of optical amplifier performance. Traditional erbium-doped fiber amplifiers (EDFA), with their high-gain characteristics, drove the widespread adoption of wavelength division multiplexing (WDM) technology in the late 20th century. However, constrained by their limited gain bandwidth in the C-band and L-band along with insufficient noise performance, EDFA have gradually struggled to meet the demands of high-speed, large-capacity communication systems. In contrast, Raman fiber amplifiers offer advantages including wide bandwidth, low noise figure, and suppression capability against fiber nonlinear effects [1]. Since the early 21st century, distributed Raman fiber amplifiers have progressively replaced EDFAs as key devices for extending unrepeatered transmission distances[2][3].

However, technical challenges still persist. For instance, higher costs, the conflict between algorithmic complexity and real-time performance leading to limited system efficiency, among others [4]. In response to these issues, researchers have gained clearer direction for the optimized design of Raman fiber amplifiers.

This paper briefly describes the fundamental working principles of Raman fiber amplification, summarize a cascaded improved Raman fiber amplifier design based on the Wild Horse Optimizer (WHO) algorithm, a Raman fiber amplifier design incorporating neural networks and the Artificial Bee Colony (ABC) algorithm, as well as a second-order Raman fiber amplifier solution based on CNN-LSTM,the Hippocampus Optimization Algorithm (HOA) and Optimization scheme for long-distance optical transmission system based on distributed Raman fiber amplifier. In terms of design optimization for Raman fiber amplifiers, this work summarizes several different design and optimization approaches.

THE BASIC WORKING PRINCIPLE OF ROMAN FIBER AMPLIFICATION

Raman scattering effect

The Raman scattering effect is an inelastic scattering phenomenon that occurs when light interacts with matter. Its defining characteristic is a slight frequency shift (Raman shift) in the scattered light relative to the incident light. The underlying physical mechanism involves energy transfer between an incident photon and an optical phonon (fiber vibration mode). This interaction generates two distinct scattered light components: Stokes scattering(lower frequency) and anti-Stokes scatterin(higher frequency) [5].

Raman fiber amplifier

In principle, Raman lasers utilize stimulated Raman scattering (SRS) to generate optical gain [1]. When intense pump light propagates through an optical fiber, it interacts with the fiber material, whereby a portion of its energy is transferred to the signal light through nonlinear Raman scattering, thereby achieving signal amplification [1]. Raman fiber amplifiers exhibit distinctive characteristics including broad bandwidth, low noise, and flexible gain control. Optimization of their algorithms plays a crucial role in enhancing the amplifier's efficiency by optimizing signal wavelengths and pump configurations.

CASCADED IMPROVED RAMAN FIBER AMPLIFIER DESIGN BASED ON WILD HORSE OPTIMIZATION ALGORITHM

The Wild Horse Optimizer algorithm

The Wild Horse Optimizer (WHO) algorithm primarily simulates the social behaviors of wild horses, including leadership, following, and foraging, to search for optimal solutions. This approach demonstrates significant advantages in optimization capability and convergence speed [6].

In the population initialization phase, the algorithm divides the population into multiple groups, with each group consisting of one stallion (dominant male), several mares, and foals. For a total population size of N and a stallion percentage of PS, the number of groups (G) is calculated as $G = N \times PS$. The remaining individuals are then evenly distributed among these groups.

Structural optimization of Raman fiber amplifier

In the primary amplification stage of the Raman fiber amplifier, signal light consisting of 100 wavelength channels (λi, 1530-1630 nm bandwidth) and four pump sources ($\lambda p11$-$\lambda p14$) are coupled into L1 km of erbium-doped tellurite fiber through an optical multiplexer (OMU), achieving signal amplification via Raman scattering. Residual pump light is then filtered out by an optical demultiplexer (ODU).

The secondary amplification stage employs another four pump sources ($\lambda p21$-$\lambda p24$), injecting new pump light into L2 km of fiber for secondary signal amplification, with the final output obtained through the ODU [6].

For the optimized design, wavelength-proximate pump lights from both stages are combined (e.g., $\lambda p13/\lambda p23$ merged into $\lambda p3$, $\lambda p14/\lambda p24$ merged into $\lambda p4$). This approach maintains structural efficiency while reducing both the number of required pump sources and overall system costs [6].

Application of Wild Horse Optimization Algorithm in Raman Fiber Amplifier

The cascaded improved Raman fiber amplifier (RFA) utilizes the Wild Horse Optimizer (WHO) algorithm to optimize key parameters, including pump power at each stage, transmission medium length, and noise characteristics. This optimization aims to achieve maximum output gain while maintaining low gain flatness [6].

Advantages of Cascade Improved Raman Fiber Amplifier with Wild Horse Optimization Algorithm

Firstly, the Wild Horse Optimizer (WHO) algorithm effectively addresses the multi-parameter cooperative optimization problem in cascaded Raman amplifiers through its grouping mechanism and dynamic leadership selection strategy. This approach significantly enhances the multi-objective optimization capability of Raman fiber amplifiers [6].

Secondly, by dynamically adjusting pump wavelength and power distribution combined with the predictive model of CNN-LSTM networks, the WHO algorithm can compensate for gain fluctuations in real time. This improves gain flatness and optimizes noise performance to a certain extent [6][7].

Furthermore, to tackle the dynamic signal power variations in dense wavelength division multiplexing (DWDM) systems, the WHO's grouped grazing mechanism enables rapid response to channel state changes. Its adaptive coefficients (e.g., Time-Dependent Rate, TDR) decrease with iteration counts, gradually shifting the algorithm from global exploration (e.g., pump combination search) to localized fine-tuning (e.g., single-stage gain equalization), thereby adapting to complex channel environments [6].

Finally, the WHO algorithm reduces dependence on high-power pump sources ($\geqslant$200 mW) and complex equalizers through intelligent parameter optimization. Consequently, it lowers both the design and operational maintenance costs originally required for high-power pump configurations [6].

Defects of Cascade Improved Raman Fiber Amplifier with Wild Horse Optimization Algorithm

First, the grouping mechanism of the Wild Horse Optimizer (WHO) requires maintaining multiple population states, resulting in relatively high computational complexity. Particularly in cascaded systems, where parameter dimensions grow exponentially, this may cause real-time response delays, making it difficult to meet millisecond-level dynamic channel allocation requirements.

Second, although WHO improves gain flatness, the total gain bandwidth of cascaded Raman amplifiers remains constrained by the wavelength coverage range of pump sources.

Finally, WHO relies on high-precision prediction models (e.g., CNN-LSTM) to provide initial parameter ranges. Insufficient training data or abrupt changes in fiber link characteristics may cause the algorithm to converge to local optima.

In summary, while the WHO-based cascaded improved design demonstrates significant advantages in gain control, noise suppression, and multi-objective optimization, its computational complexity and practical applicability still require further breakthroughs.

RAMAN FIBER AMPLIFIER BASED ON NEURAL NETWORK AND ARTIFICIAL BEE COLONY ALGORITHM

Application of Neural Networks in Raman Fiber Amplifier

The backpropagation (BP) neural network adopts a multilayer feedforward structure, which minimizes the mean square error through iterative adjustment of weights and thresholds. The input consists of pump parameters, while the output corresponds to the Raman gains of 51 signal channels. The hidden layer establishes a nonlinear mapping relationship between the inputs and outputs.

The network computation involves both forward and backward calculations.Forward calculation: Data propagates through the hidden layer to the output layer.Backward calculation: If output deviations exist, error signals are backpropagated to dynamically adjust the weights until an optimal weight configuration is achieved [8].

Once fully trained, this model can accurately predict gain values from pump parameters, establishing a reliable mapping relationship [8].

Artificial Bee Colony

The Artificial Bee Colony (ABC) algorithm is a swarm intelligence optimization method that simulates the foraging behavior of honeybees [8]. When applied to the optimization of Raman fiber amplifiers, this algorithm demonstrates several advantageous characteristics: Computational efficienc with simple implementation,effective balance between global exploration and local exploitation,strong robustness against local optima ,inherent parallel computing capability [9].

While the ABC algorithm typically exhibits fast convergence, its performance may degrade in high-dimensional optimization problems, potentially requiring integration with complementary strategies in practical applications.

Raman fiber amplifier based on neural network and artificial bee colony algorithm

The integration of BP neural network technology in Raman fiber amplifier optimization design provides an accurate and efficient method for net gain calculation, eliminating the need to solve complex Raman coupled equations [8]. When the target gain and flatness requirements are met, incorporating the trained BP neural network model into the Artificial Bee Colony (ABC) algorithm can further enhance the overall optimization efficiency [8].

Advantages and Disadvantages

This hybrid approach significantly improves the computational efficiency of Raman amplification. However, the combined architecture of the neural network and ABC algorithm introduces additional complexity, as it requires careful coordination of parameters between both algorithms. This not only increases system complexity and debugging difficulty but may also lead to potential algorithmic conflicts and other instability factors.

DESIGN OF SECOND-ORDER RAMAN FIBER AMPLIFIER BASED ON CNN-LSTM AND SEA HORSE OPTIMIZATION ALGORITHM

CNN-LSTM

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The CNN-LSTM model combines convolutional neural networks (CNN) and long short-term memory networks (LSTM) to model and optimize the performance of second-order Raman fiber amplifiers [7].CNN's spatial processing capability: Utilizing convolutional kernels to extract local features from structured data, enabling automatic learning of hierarchical representations while reducing parameter dimensionality.LSTM's temporal modeling strength: Effectively capturing time-series dependencies, making it particularly suitable for modeling dynamic amplification behaviors.

Sea horse optimizer algorithm

The Sea Horse Optimizer (SHO) is a bio-inspired metaheuristic algorithm that simulates the foraging behavior of sea horses. Key characteristics include:Balanced exploration-exploitation: Maintains effective equilibrium between global search and local optimization.Broad applicability: Demonstrated effectiveness in solving various complex nonlinear optimization problems.Implementation in amplifier design: Specifically employed to optimize both power distribution and wavelength configuration of dual-stage pump units in second-order Raman amplifiers.

This integrated approach addresses both the spatial-temporal modeling requirements of Raman amplification dynamics and the complex multi-parameter optimization challenges in amplifier design.

Advantages of second-order Raman fiber amplifier design based on CNN-LSTM and sea horse optimization algorithm

The CNN-LSTM model demonstrates capability in predicting critical fiber conditions (e.g., temperature variations, loss fluctuations), while the Sea Horse Optimizer (SHO) dynamically adjusts pumping strategies to enhance adaptive compensation. This joint optimization approach effectively mitigates the impact of double Rayleigh scattering noise on signal quality [7].

Disadvantages of second-order Raman fiber amplifier design based on CNN-LSTM and sea horse optimization algorithm

The hardware implementation requires high-performance embedded systems to support real-time control of multi-stage pumping modules (e.g., 13xx/14xx nm lasers) in second-order FRA systems, while the model's generalizability may be limited when training data is specific to particular fiber types (e.g., dispersion-compensating fibers), potentially hindering its application to other fiber varieties; moreover, parameter sensitivity significantly impacts performance, as SHO hyperparameters (including roaming step size and reproduction rate) require meticulous tuning to avoid slow convergence or premature convergence, and the long-term dependency issues inherent in LSTM networks may introduce delays in pump power adjustments, consequently reducing the system's dynamic response speed.

OPTIMIZATION SCHEME FOR LONG-DISTANCE OPTICAL TRANSMISSION SYSTEM BASED ON DISTRIBUTED RAMAN FIBER AMPLIFIER

The study reveals that in various optical fiber transmission systems, whether for long-haul or short-reach applications, the implementation of a bidirectional second-order distributed Raman pumping (BiDP) scheme with a symmetric configuration can significantly enhance the optical signal-to-noise ratio (OSNR) performance at the receiver end under the majority of operating conditions. This improvement is achieved while maintaining equivalent nonlinear effects through meticulous adjustment of first-order pump wavelengths and optimized allocation of the power ratio between first- and second-order pumps [10].

However, it must be emphasized that when double Rayleigh backscattering (DRB) noise becomes substantially pronounced within the transmission system, the conventional BiDP scheme encounters performance limitations. Under such circumstances, hybrid amplification architectures (e.g., Raman-EDFA hybrid amplifiers) demonstrate superior performance advantages [10].This conclusion not only validates the superiority of BiDP technology under standard conditions but also provides a viable solution for mitigating DRB noise challenges encountered in engineering practice.

Furthermore, the parameter optimization methodology employed in this design—particularly the precise control strategies for pump wavelengths and power ratios—offers valuable insights and technical pathways for addressing linear impairment issues in optical communication systems. These findings hold significant practical implications for the design and optimization of real-world systems.

CONCLUSION

With the widespread adoption of 5G and cloud computing, optical communication systems face surging demands for bandwidth and transmission rates. This paper reviews optimization schemes for Raman fiber amplifiers (RFAs), particularly those based on the Wild Horse Optimizer (WHO) algorithm, with experimental results demonstrating significant improvements in signal gain, gain flatness, and noise figure reduction—providing critical technical support for high-speed optical networks.

However, current solutions still face challenges, including efficiency degradation due to algorithmic complexity and limitations in application scenarios. Future research on RFAs will focus on three key areas: development of novel optimization algorithms, integration of deep learning techniques, and suppression of nonlinear distortions, ultimately driving the evolution toward intelligent optical networks.

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