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Optimization of Multi-Pump Raman Amplifier in Ultra-Wideband WDM Systems: A Review

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KEYWORDS
Machine learning enabled Raman amplification; Ultra-wide band WDM transmission; Hybrid Raman EDFA systems; Quantum classical reinforcement learning

ABSTRACT
The recent increase in interest in Multi Pump Raman Amplifier (MPRA) has been an important field of research in terms of the surge in the demand for broadband and high-capacity optical communications in Wavelength Division Multiplexing (WDM) systems. This review aims to describe a summary of 37 recent articles published on the design, modeling and optimization of Raman amplification in current optical communication systems based on WDM in terms of strengths, limitations and gaps in knowledge. The reviewed articles fall into three major directions: (1) gain and noise figure (NF) optimization strategies, (2) machine learning-based optimization and adaptive control strategies, and (3) quantum and hybrid quantum-classical reinforcement learning systems. The architectural needs of RAs to enable the transmission of WDM systems still offer possibilities to the researchers, and it has the ability of distributing, broadband optical gain with lower noise figures (NF) and flexibility across a variety of spectral bands. Recent explored approaches to machine learning (ML) and evolutionary optimizations to rapid estimation of pump powers will result in solutions enabling the inverse design of pump powers to arbitrary shaped Raman gain profiles, and the production of adaptive pump powers in ultra-wideband (UWB) WDM systems. ML frameworks such as neural networks, particle swarm optimization (PSO), and differential evolution (DE) demonstrate minimal prediction errors with respect to an effective consumption of pump powers to operate the Raman amplifiers. Multi-band programmable amplifier designs, which act as a combination of the hybrid Raman-EDFA designs, enhance optical signal-to-noise ratio (OSNR) and transmission capacity. Recent work has focused on applying quantum reinforcement learning (QRL) methods to improve scalability and convergence of high-dimensional optimization problems. In general, the review points to a shift toward adaptive real-time control, the combination of ISRS-aware optimization, and the hybrid quantum-classical smart schemes of scalable and energy-efficient ultra-wideband optical networks.

1. INTRODUCTION

As optical networks continue to require more transmission capacity, there has been increased investigation into the application of Raman amplification. This method is capable of providing long-distance, distributed gain along with very little increase in noise [1]. The use of Mult- pumped Raman amplification (MPRA) techniques was shown to produce a relatively flat-gain response over large-printing wavelength division multiplexing (WDM) transmission bands by using multiple pump wavelengths and, in general, Mult- pumping helps improve the optical signal-to-noise ratio (OSNR) and suppress nonlinear degradation. Furthermore, researchers investigating the use of cascade or series RAMAN pumping configurations have found that by properly arranging the pumps in series to produce greater than 46 dB gain, OSNR and output power capabilities increase by at least 50% beyond those attained through standard RAMAN amplification design systems [2]. In recent years, also related to these advances, machine learning models of RAMAN amplifiers (RAMAN) have been developed and have emerged as a valid method of developing inverse designs for RAMAN AMP. Recent successes have been achieved using machine learning (ML) such as neural networks, particle swarm optimization (PSO), and differential evolution (DE) to enhance the shape of gain ripple while minimizing the amount of pump power required and obtaining very close-to-perfect shaping of gain characteristics across the S-, C- and L-bands [3], [4], [5]. Recently published experimental results confirm the successful application of ML-assisted inverse designs to realize gain control for the practical link. Extensions of this research have created new hybrid Raman-EDFA amplifiers that have successfully established a flat gain profile in the C-band, whereas the variation of gain ripple in these systems has been measured at less than 1dB [6]. In addition, multi-band, programmable Raman amplifiers have been developed, which can provide an adaptive gain across a number of different wavelength bands [7]; also, non-fiber-specific machine-learning models have been developed to allow for a generalization of the gain for different optical transmission scenarios, achieving higher prediction accuracy and a decrease in training times [8]. In conjunction with these efforts, the application of reinforcement learning and hybrid classical-quantum models to optimize sequential-latency decision processes for optical networks has been investigated. Quantum deep reinforcement learning provides superior speed of convergence and blocking probability performance compared with classical reinforcement learning in the application of autonomous optical networking systems. Various hybrid classical-quantum reinforcement learning architectures have been realized utilizing latent observation spaces and multi-agent setups resulting in improved efficiency due to reductions in both sampling and reward variances [9], [10]. These contributions indicate the progressive convergence of intelligent control at the layer network level with the physical layer Raman amplification technology. The literature review indicates that Wideband Wavelength Division Multiplexing (WDM) optical communications systems require a means of transferring the optical amplification that supports wide-band transmissions with a high degree of realism. The development of Raman Scattering (SRS) has opened up the potential to provide distributed amplification as a nonlinear effect, and there is multi-modal flexibility in regard to wavelength, and a source of fiber-based optical elements that are already available, making the potential to use the SRS-based amplification anywhere within the existing telecommunication infrastructure practical. Most studies of Multiple Pumped Raman Amplifiers (MPRAs) have focused on providing flat gain profiles across wideband WDM communications [1, 2, 6, 11, 12]. There is a wide variety of possible designs for Multi-pumped-Raman-Amplifiers (MPRA), including lumped, distributed, hybrid, and multi-band programmable gain Raman amplifiers, which aim to optimise performance while addressing the various challenges associated with amplification, such as Amplified Spontaneous Emission (ASE) noise and pump depletion and nonlinear distortion [13, 14, 15, 16, 17].

2. RELATED SURVEY

Amplification plays a curricula role in wideband WDM optical communication systems that employ environmentally sustainable optical gain mechanisms across broad spectral ranges. Among the various nonlinear effects, stimulated Raman scattering (SRS) has proven particularly advantageous due to its capability to provide distributed amplification, compatibility with existing fiber infrastructure, and flexibility in achieving over a wide set of wavelengths [1], [2], [6], [11], [12]. A variety of Raman amplifier designs have been advanced by researchers, including lumped, distributed, hybrid, multi-band programmable gain designs which aim to enhance total performance, while mitigating the effects of ASE noise, pump depletion, and nonlinear distortion [13], [14], [15], [16], [17]. Nevertheless, the optimizing pump powers and wavelengths represents a complex high-dimensional problem. The nonlinear coupling among wavelength channels often lead to inter-channel crosstalk, which complicates analytical and numerical optimization. Figure 1 illustrates a diagram of an Optical Communication Link with Distributed Raman Amplification. The transmitter drives the Optical Signal through a single-mode fiber (SMF) link or span. Instead of being located at the end of a link like a discrete amplifier, the transmission fiber generates the Raman Gain (i.e. amplifying effect on the Optical Signal) by injecting the pump light (Pump Lasers) into the fiber from both ends. The portion of pump light that travels with the same direction as the Optical Signal is referred to as Forward Pump light; whereas, the portion of pump light that travels against the direction of the Optical Signal is referred to as Backward Pump light. Since Pump Light is evenly distributed throughout the entire length of the transmission fiber, the Optical Communication Link operates under the principle of Distributed Raman Amplification.

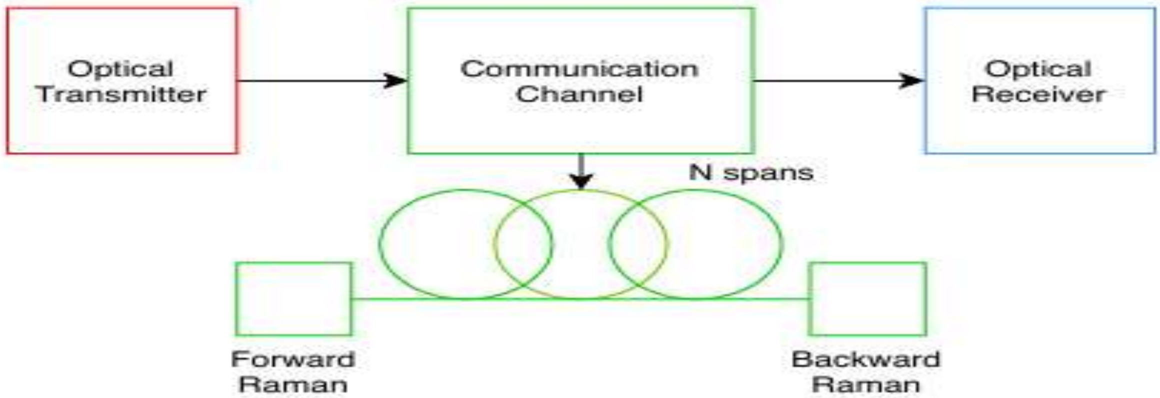

Fig. 1. A simplified optical transmission system consisting of a transmitter, a communication channel consisting of multiple spans of fibers and forward and backward Raman pumps, and a receive [3].

To address these challenges, researchers have adopted heuristic and inverse-design techniques such as simulated annealing, genetic algorithms, and particle swarm optimization (PSO); as well as machine-learning (ML)-based optimization methods, to achieve improved Raman gain flatness and energy efficiency [2], [6], [8], [11], [22],[24], [25]. More recent work has extended these optimization efforts towards ultra-wideband transmission, introducing techniques such as distributed Raman amplification with inverse SRS, optical phase conjugation (OPC), and optimization of asymmetries in the C+L bands, enabling gain bandwidths exceeding 10 THz [18] ,[20], [24], [27], [31]. The review is organized into the following categories:

2.1. Performance Analysis of Raman Amplifiers:

The researches that were reviewed on Raman amplifier architectures generally share the aim of achieving broadband and flat gain while also boosting the optical signal-to-noise ratio (OSNR). It has been shown that backward-pumped configurations reliably minimize the noise figure and improve system stability [15]. in parallel, multi-pump configurations can extend the usable gain bandwidth to beyond 10 THz in optimized scenarios [2], [18]. The development of universal modeling approaches [17] and inverse design solutions [22], [23], has further advanced the flexibility associated with Raman amplifier modeling and or optimization of performance parameters. On the other hand, stimulated Raman scattering (SRS) still poses actual performance limitations to overall operation due to power depletion among adjacent WDM channels [20]. More recent developments, such as programmable multi-band Raman amplifiers, have provided exciting prospects for ultra-wideband optical transmission, but precise control of pump-power remains a practical challenge related to unresolved optimization of discrete optical components [24].

Table 1. summarizes the principal research tends and outlines corresponding future directions.

Title	Author	objectives	Method	Results	Discus-sion Conclu-sions	Strong-est	Weakness

Backward Pumped Distributed Raman Amplifier Enhanced[15]	Mustafa, F. M.; Kholidy, H. A.; et al. 2023	This study investigates performance of backward-pumped distributed Raman amplifiers.	Simulation and experimental validation of DRA with backward pumping.	Achieved enhanced gain distribution with improved OSNR.	Backward pumping reduces nonlinearities and noise figure compared to forward pumping.	High OSNR and low noise figure.	Complexity of pump configura-tion.
Enhanced Gain Raman Amplifiers Using Different Pumping Schemes[2]	Fathy M. Mustafa, et al. 2023	To compare different pumping schemes in Raman amplifiers.	Simula-tion and experi-mental validation of DRA with backward pumping.	Multi-pump forward/backward schemes achieved >10 THz flat gain.	Optimal schemes improve flatness and reduce tilt.	Wide-band coverage with flatness.	High power consump-tion.
A Universal Framework for Solving SRS[17]	Yuchen Song; Min Zhang; et al.2024	To develop a universal modeling framework for stimulated Raman scattering.	Proposed a mathematical model solving SRS in arbitrary conditions	Framework accurately predicts Raman gain spectra.	Provides generalized method for amplifier design.	Univer-sality of frame-work.	Computa-tional complexity.
Asymmetry Optimization for 10 THz OPC Transmission over C+L[18]	Paweł Rosa; et al.2023	To enhance OPC-assisted C+L transmis-sion using Raman asymmetry optimiza-tion.	Simulations of distributed Raman amplification with OPC.	Achieved 10 THz bandwidth with flat gain.	Asymmetry reduces nonlinear penalty.	Wideband reach extension.	Sensitive to pump fluctuations.
Detailed Performance Investigation and BER Characterization [19]	Arwa A. Moosa; et al.2023	To investigate BER impact of Raman amplification.	Experimental setup with multi-channel WDM signals.	Significant BER improvement with distributed amplification.	Raman amplifiers extend transmis-sion reach.	BER reduction and improved reach.	Requires high pump power.
Effect of Fiber Stimulated Raman Scattering[20]	Arwa A. Moosa; et al.2022	Study SRS effects on optical system performance.	Analytical + experi-ment	Power transfer penalties	Need manage-ment	Identifies impair-ments	Signal degradation
High Gain DRA for Orbital Angular Momentum[21]	Yuchen Zhang;et al.2024	Study SRS effects on optical system	Experi-ment OAM channels	High gain, low cross-talk	Supports OAM multiplex-ing	OAM enabled	Complex system

		perform-ance.					
Inverse Design of Raman Amplifier[22]	Mehran Soltani; et al.2021	Apply inverse design for Raman amplifier optimiza-tion.	Numerical optimiza-tion	Flat programmable gain	Adaptive amplifiers	Flexib-ility	Expensive computation
Modeling Optical Amplifiers[23]	Frances co Da Ros;et al.2023	Extend modeling of Raman amplifiers to full systems.	Inverse + system sims	Improved network optimization	System-wide relevance	System perspec-tive	Implementat ion complexity
Multi-Band Programmable Gain Raman Amplifier[24]	Uiara Celine de Moura; et al.2020	Realize multi-band Raman amplifiers with program-able gain.	Experi-mental setup	Flat gain multi-band	Supports wideband	Flexibil-ity	Pump complexity

Table 1 compares the performance-based works provided, and it can be seen that backward-pumped distributed Raman amplifiers are always known to have lower noise figures and higher OSNR than forward-pumping schemes. Multi-pump designs reach to the gain bandwidth of 10 THz but this achievement comes at the cost of greater pump complexity and power expenditure. More so, nonlinear impairments including SRS are typically considered alone and not considered alongside gain flatness and OSNR. This implies that the gain stability, nonlinear mitigation and noise performance properties are not yet co-optimized in the system-wide level although the performances have been demonstrated to improve.

2.2. Optimization of Multi-Pump Raman Gain:

Because several pump lasers engage in nonlinear interactions inside the fiber, the optimization of multi-pump Raman amplifiers has been an important area of study.Initial reports showed that the selection of appropriate pump powers and wavelengths produced a flat Raman-gain spectrum, with low ripple and stable output power [2], [3]. Additional simulation results suggested that an increased number of pumps could enhance bandwidth of amplification and also assist in design flexibility, although it also added some complexity to the optimization problem [6], [29]. To help with these challenges, researchers applied inverse-design and heuristic optimization techniques like genetic algorithms, particle swarm optimization (PSO), and differential evolution (DE) that could effectively indicate the pump configurations for the desired outcomes of flattening the gain spectrum [8], [22], [23]. Physical experimental demonstrations confirmed that in a physical, machine learning-based Raman amplifier design, data-driven physical models could reproduce the Raman gain with less than or equal to absolute errors that were no greater than 0.5 dB, supporting the applicability of these processes in a typical setup for transmission links [11]. More recently, hybrid optimization methods were introduced, which used offline training for accuracy with online differential to monitor changes in actual time [25]. Additionally, multi-band reconfigurable Raman amplifiers expanded these optimization concepts to ultra-wideband WDM systems, allowing flexible shaping of the gain and pump power for multiple stated wavelength bands [24].

Title	**Authors**	**objectives**	**Method**	**Results**	**Discussion Conclusions**	**Strongest**	**Weakness**

Optimal Design of Flat-Gain Wide-Band Raman Amplifier[2]	Victor E. Perlin, et al. 2002	Design Raman amplifier with flat gain over wideband.	Optimization of multi-pump powers and wavelengths.	Achieved flat gain <0.5 dB ripple.	Multi-pump optimization effective for WDM.	Excellent flatness.	High computational effort.
Net Effective Gain of Multi-Pumping Raman[3]	Abd El-Naser A. Mohammed.2007	Analyze net gain performance with multiple pumps.	Theoretical + experimental validation.	Improved effective gain with multi-pump.	Pump interplay impacts net efficiency.	Balance between pumps.	Sensitive to pump power fluctuation.
Investigations on Multi-Pumped Fiber Raman Amplifier[6]	K. Singh, M. S. Patterh,et al.2012	Evaluate performance of multi-pumped FRAs.	Simulations across multiple channels.	Wider gain bandwidth achieved.	Multi-pump increases flexibility.	Wide coverage.	Pump design complexity.
Flexible Raman Amplifier Optimization (ML-aided Physical Model)[8]	M. P. Yankov, F. D. Ros,et al. 2023	Apply ML-aided physical models for pump optimization.	Machine learning + physical simulation.	Improved optimization efficiency.	ML speeds up inverse design.	Fast and accurate.	Requires training data.
Experimental Validation of ML-based Raman Amplifier Design[11]	Soltani, Mehran,et al.2022	Validate ML models for Raman amplifier design.	Experimental demonstration with ML predictions.	Accurate gain shaping with <0.2 dB error.	ML improves adaptability.	Strong experimental support.	Data-driven limitations.
Inverse Design of Raman Amplifier[22]	Mehran Soltani,et al. 2021	Apply inverse design for Raman amplifier optimization.	Numerical optimization	Flat programmable gain	Adaptive amplifiers	Flexibility	Expensive computation
Modeling Optical Amplifiers[23]	Francesco Da Ros,et al.2023	Extend modeling of Raman amplifiers to full systems.	Inverse + system sims	Improved network optimization	System-wide relevance	System perspective	Implementation complexity
Multi-Band Programmable Gain Raman	Uiara Celine de Moura,et al.2020	Realize multi-band Raman amplifiers with	Experimental setup	Flat gain multi-band	Supports wideband	Flexibility	Pump complexity

Amplifier[24]		programmable gain.					
Online vs Offline Optimization of Raman Amplifiers[25]	Uiara C. de Moura,et al.2022	Compare online vs offline optimization.	Hybrid optimization methods.	Online adapts to dynamic changes.	Offline accurate but slower.	Adaptability (online).	Stability trade-off.
Performance Optimization of Multi-Pumped Raman Amplifier[29]	Mohsen Katebi Jahromi, et al.2016	Optimize multi-pump configuration.	Analytical + numerical optimization.	Higher flatness and efficiency.	Optimized pumps reduce penalties.	Effective optimization.	Computational overhead.

As observed by comparing the optimization strategies that were summarized and presented in Table 2, the gain ripple of less than 0.5 dB has been attained by controlling the pump powers and the wavelengths used, and this indicates the validity of the multi-pump optimization approach. The flexibility of the gain-shaping can be greatly increased with the help of the heuristic and inverse-design methods, such as PSO and CNN-based processes. The majority of methods are however computationally expensive and are mainly performed offline. The higher the number of pumps, the higher the expansion of the parameter space, which becomes more and more unscalable and can no longer be used in real time. Moreover, dynamic channel loading situations are hardly included in optimization goals. Consequently, despite the current high accuracy of the flatness of statical gain, the real-time adaptive multi-pump optimization is still an open research problem.

2.3. Machine Learning–Based Raman Design:

Recently, machine learning (ML) has emerged as a central approach to improving the performance and design of Raman amplifiers. The development of fiber-agnostic ML models has enabled transfer learning between fiber types, significantly reducing the amount of retraining necessary for each configuration [10]. In summary, ML-assisted Raman design has been shown to scale, adapt, and be efficient, however, the requirement for large data sets that span the design space is still a limitation that requires ongoing investigation [8], [10], [11], [23].

Title	**Authors**	**objectives**	**Method**	**Results**	**Discussion Conclusions**	**Strongest**	**Weakness**
Flexible Raman Amplifier Optimization (ML-aided Physical Model)[8]	M. P. Yankov,et al.2023	Apply ML-aided physical models for pump optimization.	Machine learning + physical simulation.	Improved optimiza-tion efficiency.	ML speeds up inverse design.	Fast and accurate.	Requires training data.
Fiber-Agnostic ML-Based Raman Models[10]	de Moura,et al. 2022	Develop fiber-agnostic models.	Transfer learning	Works across fibers	Improves flexibility	Generaliza-tion	Retraining cost

Experimental Validation of ML-based Raman Amplifier Design[11]	Soltani, Mehran,et al.2022	Validate ML models for Raman amplifier design.	Experi-mental demonstra-tion with ML predictions.	Accurate gain shaping with <0.2 dB error.	ML improves adaptability.	Strong experi-mental support.	Data-driven limitations.
Multi-Band Programmable Gain Raman Amplifier[24]	Uiara Celine de Moura,et al.2020	Realize multi-band Raman amplifiers with program-able gain.	Experi-mental setup	Flat gain multi-band	Supports wideband	Flexibility	Pump complex-ity
Online vs Offline Optimization of Raman Amplifiers[25]	Uiara C. de Moura,et al.2022	Compare online vs offline optimization.	Hybrid optimization methods.	Online adapts to dynamic changes.	Offline accurate but slower.	Adaptab-ility (online).	Stability trade-off.

A critical examination of the ML-based design approaches utilized in the analysis of the Raman design shown in Table 3 indicates that the data-driven models consume a lot less time in the computation than the traditional numerical optimization. Nevertheless, the majority of ML methods are oriented more towards prediction of statical gains, than adaptive control using closed loop. The coverage of training data is strongly dependent on their performance, and their validation is only experimental to certain settings. Due to this fact, although ML enhances efficiency in modeling the gain and inverse design, the application of it to real-time adaptive physical-layer control of Raman has not been well developed.

2.4. Ultra-Wideband WDM & ISRS/OPC

Recent years have seen increasing research activity in Raman amplification for ultra-wideband WDM transmission. By using distributed Raman amplification with optimized asymmetry, researchers have demonstrated C+L band operation with a total gain bandwidth exceeding 10 THz and considerable viability for ultra-high-capacity optical communication systems (19). Bit error rate (BER) characterizations showed that distributed Raman reduced transmission penalties in high-capacity links (20). However, stimulated Raman scattering was a nonlinear penalty introduced by Raman amplification that transferred power between adjacent channels (21). Optical phase conjugation alongside distributed Raman amplification was suggested as a remedy and yielded near complete compensation for the nonlinear effects (27). The new transmission formats and multi-core fibers allowed further enhancement of system performance (30]. Table 4 summarizes the principal research tends and outlines corresponding future directions.

Title	**Authors**	**objectives**	**Method**	**Results**	**Discussion Conclu-sions**	**Strong-est**	**Weak-ness**
Asymmetry Optimization for 10 THz OPC Transmission[18]	Paweł Rosa,et al. 2023	Optimize C+L band OPC with Raman.	Simulation	10 THz bandwidth	Non-linearity reduction	Wide-band reach	Pump sensitivity

Detailed Performance Investigation and BER Characterization of Raman Amplifiers[19]	Arwa A. Moosa,2023	Investigate BER improve-ment.	Investigate BER improve-ment.	BER improved	Transmission reach extended	Low BER	Needs high pump
Effect of Stimulated Raman Scattering[20]	Arwa A. Moosa,et al.2022	Study SRS impairments.	Analysis + experi-ment	Power transfer	SRS impact critical	Identif-ies penalt-ies	Signal degrada-tion
Parallel WDM Signal Transmission and Dispersion Compensation Enabled by Soliton Microcombs and Micro rings.[26]	Yuanbin Liu; Hongyi Zhang,et al.2024	Parallel WDM with Raman.	Experi-mental	Disper-sion compensa-tion	New comb sources	Novel formats	Low efficien-cy Thermal control

Table 4 results demonstrate that ultra-wideband transmission over the C+L bands with gain bandwidths over 10 THz have been made possible by asymmetric pumping and distributed Raman amplification. Optical phase conjugation (OP C) further enhances BER in long distance systems. Comparative analysis of the configurations reveals that the configurations are very sensitive to the stability of power to the pumps and the spectral imbalance. Whilst the effects of ISRS have been studied in various papers, mitigation is mostly seen as a corrective action as opposed to being integrated into the optimization process. Additionally, the majority of the works make an assumption of fixed channel loading conditions, and thus they cannot be applied to real-life dynamic WDM conditions. Thus, even with substantial improvement in the development of bandwidth, a common framework that can collectively deal with ultra-wideband gain shaping, ISRS-conscious optimization and adaptive pump control in dynamic environments is yet to be released.

2.5. Hybrid/Quantum RL for Optical Networks

Reinforcement learning (RL) and quantum-enhanced approaches have been explored to improve multi-pump Raman amplifiers and advanced optical networks. Hybrid quantum classical reinforcement learning techniques have shown more rapid convergence and steady improvement in multi-agent settings [34],[36]. Quantum deep Q-learning with distributed prioritized replay exhibited robustness and smaller probability of blocking [35]. Furthermore, quantum reinforcement learning has been applied to resource allocation and rare event optimization in classical systems with abundant exploration capability [37]. Initial works on RL experiences in optical communication provided the groundwork in teaching an AI-agent to make successive decision-making processes for amplifiers and networks optimization. Overall, these contributions suggest that hybrid quantum classical RL can complement ML routing optimization of Raman amplifiers with addressing aspects of complexity, scalability, and adaptation in ultra-wideband WDM. Table 5 summarizes the principal research tends and outlines corresponding future directions.

Title	**Authors**	**objectives**	**Method**	**Results**	**Discussion Conclusions**	**Strongest**	**Weakness**
Deep RL for Quantum Systems[32]	Valeria Cimini,et al.2023	Apply deep RL to quantum optimization.	DRL framework	Faster training	Hybrid model potential	Exploration efficiency	High resource cost

Hybrid Quantum-Classical RL in Latent Spaces[34]	Dániel T. R. Nagy,et al. 2025	Improve RL efficiency.	Hybrid latent RL	Faster convergence	Better scalability	Efficient	Stability issues
Quantum Deep Q-Learning with Distributed Replay[35]	Samuel Yen-Chi Chen,et al.2023	Enhance RL stability.	QDQN-DPER	Reduced blocking	Robust training	Stability	Complexity
Quantum RL for Rare Classical Events[37]	Alissa Wilms,et al. 2025	Optimize rare events.	Quantum RL	Improved exploration	Superior performance	Strong adaptability	Needs hardware

3. COME-OUT DRIFT AND FUTURE DIRECTIONS

This examination identifies important gaps and potential research lines in regard to optimization of Raman amplifiers and hybrid learning frameworks. When selected studies described challenges such as ISRS impairment, scalability of multi-pump configurations, and the need for adaptive control, we acknowledge that fundamental research questions and adjunct questions like device performance and system-level design. Table 6 summarizes the principal research tends and outlines corresponding future directions.

Title	Authors	Come Out Drift	Future Directions
Optimal Design of Flat-Gain Wide-Band Fiber Raman Amplifier[2]	Victor E. Perlin ,et al. 2002	Early flat-gain designs limited to narrow bands.	Extend flat-gain designs to multi-band (C+L) operation with reduced pump budgets.
Enhanced Gain Raman Amplifiers Using Different Pumping Schemes[16]	Fathy M. Mustafa, et al. 2023	Pump configuration strongly affects gain stability and OSNR.	Develop programmable pumping strategies adaptive to WDM traffic and spectral tilt.
Inverse Design of Raman Amplifier in Frequency/Time Domains [22]	Mehran Soltani,et al.2021	Inverse design effective but limited to simulation datasets.	Implement real-time, data-driven inverse design in experimental testbeds.
Online vs Offline Optimization for Raman Amplifiers[25]	Uiara C. de Moura, et al. 2022	Offline ML models achieve accuracy but lack adaptability to dynamic changes.	Develop hybrid online-offline schemes combining stability with adaptive responses.
Hybrid Quantum-Classical RL in Latent Spaces [34]	Dániel T. R. Nagy ,et al. 2025	Classical RL struggles with scalability in high-dimensional pump design.	Integrate quantum-enhanced RL for faster convergence and efficient multi-pump Raman optimization.

4. IMPORTANT RESULTS

4.1 Performance of Raman Amplifiers

• Backward-pumped distributed Raman amplifiers (DRAs) had a better noise figure and optical signal-to-noise ratio (OSNR) compared to forward-pumped configurations, confirming backwards-pumped systems could be a better choice for long-haul transmission links.

• Asymmetry optimization and optical phase conjugation (OPC) in multi-pump Raman designs achieved nearly 10 THz of flat gain throughout the C+L bands enabling ultra-wideband transmission to be achieved.

• Distributed Raman amplification (DRA) reduced the bit error rate (BER) and increased transmission reach, especially in dense WDM networks.

• The high-gain distributed Raman system also accommodated more advanced modulation formats, such as orbital angular momentum (OAM) modes, to increase the spectral efficiency.

4.2 Optimization and Inverse Design

• Gain flatness under 0.5 dB was achieved by precisely adjusting the pump powers and/or pump wavelengths in agreement with experimental verification.

• Inverse-design optimizations in time and frequency domains enabled programmable Raman gain shaping for added flexibility.

• Multi-band programmable Raman amplifiers also extended the usable operational window with bandwidths up to 17.6 THz, paving the way for next-generation ultra-low bandwidth systems.

4.3 Machine Learning

• Data-driven approaches were verified experimentally when machine-learning-driven Raman models were able to reproduce gain characteristics with a maximum absolute error under 0.5 dB within data-driven approaches.

• Fiber agnostic ML models were able to utilize transfer learning technique across different types of fibers to minimize retraining time and maximize modeling efficiency.

4.4 Ultra-Wideband and ISRS Effects

• Stimulated Raman scattering (SRS) and inter-channel power tilt have been identified as major limitations in ultra-wideband WDM transmission, especially throughout the C+L bands.

• Microcomb and microring resonator sources enabled parallel WDM transmission with intrinsic dispersion compensation, improving multi-channel stability.

• Multi-core fiber designs further increased total transmission capacity while maintaining distributed Raman gain for each core.

4.5 Hybrid and Quantum Reinforcement Learning

• Hybrid reinforcement learning (RL) models operating in latent state spaces achieved faster convergence and greater sample efficiency compared to conventional deep-RL approaches.

•Quantum deep Q-network (Q-DQN) frameworks improved learning stability and reduced network blocking, showing strong potential for intelligent resource management in optical communication environments.

•Quantum deep reinforcement learning (QDRL) frameworks improved network utilization and lowered blocking probability in optical networks.

•Quantum reinforcement learning applied to rare-event dynamics highlighted the advantages of Fourier-feature exploration.

•Reinforcement learning educational frameworks emphasized the importance of sequential decision-making as a foundation for advanced applications.

5. RESEARCH TRENDS

• Extensive and Moderate Bandwidth Utilization

Research has evolved from narrowband Raman operations to wider bandwidth use covering the S, C and L bands. Moving into narrowband Raman operation requires the creation of programmable Raman amplifier designs with the capability for adaptive gain shaping across a wider optical frequency range.

• RAMAN Design Using AI Models

The application of machine learning methods to accelerate the design of Raman amplifiers has proliferated. More specifically, transfer-learning framework designs have been employed to leverage the previous knowledge of the training designs to reduce training time and achieve more adaptable designs under different network conditions.

• Inherent Architecture Mitigation

There is an interesting body of work regarding amplifier architectures that embed some form of nonlinear distortion mitigation, such as ISRS and power with tilt, into the design optimization process. Instead of post-processing corrections, these designs included compensation throughout the modeling and training of the amplifier designs to achieve both spectral flatness and system stability.

• An Al-Quantum Hybrid Intelligence Framework

The idea of an al-type reinforcement learning (RL) combined with quantum inspired algorithms is becoming more commonplace. The hybrid intelligence framework may be advantageous as a solver for high-dimensional, multi pump Raman optimization problems at much faster convergence and less computational costs.Future Directions.

6. FUTURE DIRECTIONS

6.1 Adaptive Real-Time Control

The future research directions are to include the adaptive real-time control mechanisms that dynamically vary the pump powers and wavelengths and maintain the gain flatness and OSNR performance even in offline-optimized scenarios.

6.2 ISRS-Aware optimization structures

The inter-channel stimulated Raman scattering (ISRS) reduction aspect cannot be considered as a distinct compensation step but rather be included in the optimization process in an effort to maintain spectral flatness and transmission stability in the ultra-wideband systems.

6.3 Hybrid Quantum-Classical Reinforcement Learning

The idea of hybrid quantum-classical reinforcement learning is one of the promising directions to address high-dimensional multi-pump optimization problems and provides possible improvements in scalability and convergence efficiency, although it needs to be further verified in experiments.

7. CONCLUSION

Significant advancements have been made in the development of multi-pump Raman amplifier frameworks as well as AI-driven optimization approaches, resulting in flat ultra-wideband gain and extended transmission distances in next-generation optical networks. Nevertheless, there are several issues, particularly in means of scalability, maintaining online adaptability, and reducing the once again impact of inter-channel power tilt, due to inter-channel stimulated Raman scattering (ISRS) in wideband WDM networks. In the future, work should be focused towards investigating controllable Raman hardware combined with adaptive machine-learning (ML) and reinforcement-learning (RL) control approaches, as well as hybrid quantum (classical) reinforcement learning as exciting future directions toward smart, energy-efficient, and self-optimizing optical networks. Ultimately, the success of Raman amplification's development depends on how many different channels are available for the continued development of Raman amplification. Collaborative pathways (i.e. how many different sources or channels) of innovation and optimisation, combined with large trials, will lead to greater feasibility for Raman amplification within the next generation of optical communication systems.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تحسين أداء مضخّم رامان متعدد المضخات في أنظمة تقسيم الطول الموجي واسع النطاق فائقة الاتساع : بحث مراجعة

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الملخص

شهدت مضخمات رامان متعددة المضخات (MPRA) اهتماماً متزايداً في السنوات الأخيرة، وذلك نتيجة الارتفاع الكبير في الطلب على الاتصالات الضوئية ذات النطاق العريض والسعة العالية في أنظمة تقسيم الطول الموجي .(WDM) تهدف هذه المراجعة إلى تقديم تحليل شامل لـ 37 دراسة حديثة تناولت تصميم ونمذجة وتحسين تضخيم رامان في أنظمة الاتصالات الضوئية المعتمدة علىWDM ، مع بيان نقاط القوة والقيود والفجوات المعرفية في كل منها.تم تصنيف الدراسات المستعرضة ضمن ثلاثة اتجاهات رئيسية: (1) استراتيجيات تحسين الكسب ومعامل الضوضاء(NF) ، (2) استراتيجيات التحسين والتحكم التكيفي المعتمدة على تقنيات تعلم الآلة، (3) أنظمة التعلم التعزيزي الكمي والهجين (الكمي–الكلاسيكي).
لا تزال المتطلبات المعمارية لمضخمات رامان لتمكين نقل أنظمة WDM تتيح فرصاً بحثية واسعة، نظراً لقدرتها على توفير كسب ضوئي موزع وعريض النطاق، مع معاملات ضوضاء منخفضة ومرونة عبر نطاقات طيفية متعددة.وقد أظهرت الأساليب الحديثة المعتمدة على تعلم الآلة (ML) وخوارزميات التحسين التطوري قدرة على التقدير السريع لقدرات المضخات، مما يمكّن من التصميم العكسي لقدرات المضخات للحصول على أشكال كسب رامان مخصصة، إضافةً إلى إنتاج قدرات مضخات تكيفية في أنظمة WDM ذات النطاق العريض جداً.(UWB) كما بينت أطر تعلم الآلة مثل الشبكات العصبية الاصطناعية، وخوارزمية سرب الجسيمات (PSO)، وخوارزمية التطور التفاضلي (DE) تحقيق أخطاء تنبؤ منخفضة مع استهلاك فعال لقدرات المضخات عند تشغيل مضخمات رامان.وتسهم تصاميم المضخمات متعددة النطاقات القابلة للبرمجة، والتي تجمع بين مضخمات رامان و EDFAالهجينة، في تحسين نسبة الإشارة إلى الضوضاء الضوئية (OSNR) وزيادة سعة الإرسال.وقد ركزت الأعمال الحديثة على تطبيق أساليب التعلم التعزيزي الكمي (QRL) لتحسين قابلية التوسع وتسريع التقارب في مسائل التحسين ذات الأبعاد العالية.وبصورة عامة، تشير نتائج المراجعة إلى تحول واضح نحو أنظمة التحكم التكيفي الآني، ودمج تحسينات تأخذ تأثير التبعثر رامان المحفَّز بين القنوات (ISRS) بالحسبان، إضافةً إلى تبني مخططات ذكية هجينة كمي–كلاسيكي لتحقيق شبكات ضوئية فائقة العرض ذات كفاءة طاقية وقابلية توسع عالية.

الكلمات المفتاحية

تضخيم رامان المدعوم بالتعلم الآلي؛ نقل WDM فائق العرض؛ أنظمة رامان EDFA الهجينة؛ التعلم التعزيزي الكمي الكلاسيكي.