



A Brief Review on Future and Scope of AI and ML in Optics

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Abstract -- Artificial intelligence (AI) is transforming the development of diffractive optics through its advanced capabilities in design optimization, pattern generation, fabrication enhancement, performance forecasting, and customization. This paper provides an in depth evaluation of how AI techniques can enhance the performance of optical communication systems and networks. Initially the paper explores AI-techniques in photonic neural networks covering aspects such as Architecture Design, hardware implementation and Performance Optimization. Additionally it examines photonic integrated circuits, Optical Design and Optimization, Optical Communications and optical sensing and imaging .Finally the paper concludes by summarizing the imminent prospects and challenges in optical networking where AI is expected to play a significant role.

Keywords -- Artificial Intelligence, Machine Learning, Optics, Optical Neural Network, Photonics, Photonic Neural Network, Photonic Integrated Circuits,

I. INTRODUCTION

AI has taken significant leaps forward in recent years, evolving into a powerful technology that enables real-world applications to be more efficient and intelligent. Given the ever-growing scale and complexity of datasets, AI is increasingly being integrated into diverse scientific disciplines to facilitate fast and efficient data processing and analysis. In the photonics community, leveraging AI research assist in solving complex photonics problems has become a major research focus. AI can be incorporated into forward modeling and inverse design to approaches improve the efficiency and accuracy of photonic system analysis. Neural networks can be trained to predict the optical responses of photonic structures, based on their geometric parameters.

This enables for rapid simulation and analysis of multiple configurations without the need for computationally expensive numerical simulations.

II. KEY APPLICATION AREAS OF AI IN DIFFRACTIVE OPTICS AND PHOTONIC SYSTEMS [8]-[10]:

A. Intelligent Device & Sensor Design:

AI driven optimization techniques are used to enhance the performance of photonic devices and sensors by improving parameters devices and sensors by improving parameters such as efficiency, bandwidth and sensitivity [8].

B. Autonomous Control:

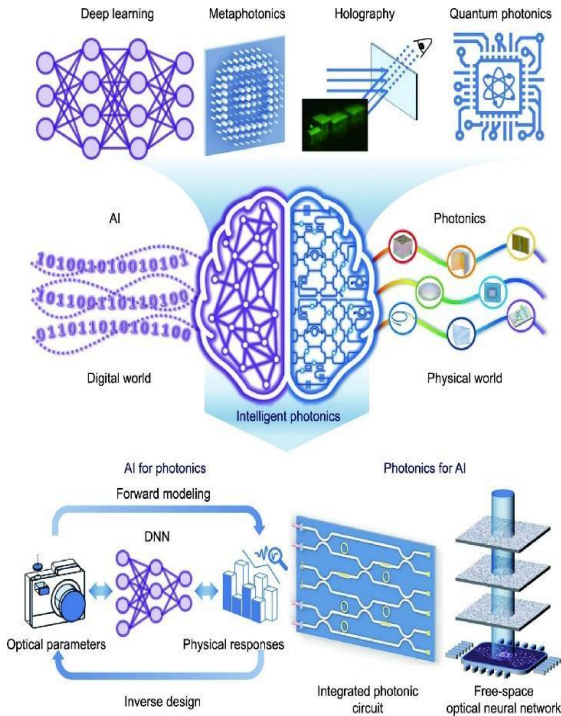
AI facilitates control in applications including laser autonomous material processing additive manufacturing, and optical networking by angling adaptive and real-time decision making processes[9].

C. AI-Enhanced Sensing & Communication:

AI enhanced optical systems are widely used in smartphone cameras, microscopy, augmented reality displays and emerging sixth generation (6G) communication technologies [10].

III. NEW OPPORTUNITIES FOR THE USE OF AI IN OPTICAL NETWORKS [11]:

AI introduces new opportunities in optical networking, including optical transmission optimization and security enhancement, automation of network management operations, efficient joint operations of communication networks and computing resources and applications in on-chip optical network.



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Fig. 1: Intelligent Photonics architecture illustrating interaction between AI and photonics system [13].

IV. ARTIFICIAL INTELLIGENCE, MACHINE LEARNING, AND DEEP LEARNING

Artificial intelligence (AI) is a broad field focused on creating machines that can mimic human intelligence including reasoning, learning, perception, and problem-solving. Within AI, **Machine Learning (ML)** enables computers to learn patterns from data without explicit programming. A further subset, **Deep Learning (DL)**, employs artificial neural networks inspired by the human brain to recognize complex patterns and make high-level decisions [2].

In recent years, deep learning has outperformed traditional ML methods across many domains, largely due to its scalability and superior accuracy. However, training deep neural networks requires massive amounts of data, which are often costly and difficult to obtain. In such cases, classical machine learning remains valuable as they offer simpler and more data efficient alternatives [2].

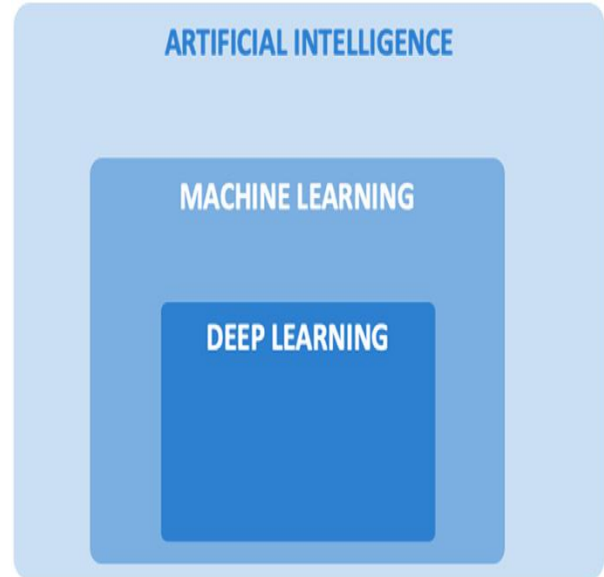


Fig. 2: Hierarchical relationship between Artificial Intelligence, Machine Learning and Deep Learning.[2]

V. OPTICAL TECHNOLOGIES MIGHT SUPPORT AI/ML WORKLOADS

The rapid growth of AI and ML workload has created stringent requirements for high-bandwidth, low-latency and energy-efficient communication within and between data centers. Several optical technologies are currently under extensive investigation to support intra- and inter- rack communication at data rates of 200G and 400G per lane.

Key enabling technologies include vertical-cavity surface-emitting lasers (VCSELs) within multimode fiber, silicon photonics, and electro-absorption modulated lasers (EMLs) with single-mode fiber [4]. These technologies offer high scalability, improved energy efficiency, and cost-effective manufacturing, making them well suited for AI driven computing infrastructures.

To further enhance system density, flexibility, and power efficiency while reducing cost and latency, the industry is exploring advanced optical transceiver packaging solutions. These include full DSP pluggable transceivers, linear-drive pluggable transceivers, and co-packaged optics. Co-packaged optics, in particular, reduce electrical interconnect lengths between switches and optical engines, which is critical for meeting the power and bandwidth demands of large scale AI clusters.



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In addition, optical circuit switching (OCS) based on micro-electro mechanical systems (MEMS) has been deployed in data centers to enable dynamic topology reconfigurations, flexible network upgrades, improved resilience and efficient traffic grooming. Such capabilities are especially beneficial for AI workloads, which often involve highly dynamic and non-uniform traffic patterns.

Thermal management is another critical consideration. Liquid cooling is increasingly adopted to maintain reliable and efficient operation of high-density optical and computing systems. Although liquid cooling is well established in high-performance computing platforms, its application in optical equipment is relatively recent and represents an important advancement for AI-enabled optical network [4].

VI. AI TECHNIQUES APPLIED TO OPTICAL NETWORKING

Artificial Intelligence (AI) focuses on the development of intelligent agents capable of perceiving network states, making decisions, and adapting their actions to optimize system performance. In optical networking, AI techniques are increasingly applied to address challenges related to network planning, control, optimization, and fault management.

The static and well-defined network environments, traditional search and optimization methods such as breadth-first search for routing and linear or mixed-integer programming for network planning have been widely used. However, as optical networks become more dynamic, large scale, and uncertain, these classical approaches often struggle to meet real-time performance requirements.

To address these challenges, metaheuristic algorithm such as simulated annealing, genetic algorithms, swarm optimization have been applied to optical network planning, light path establishment, resource allocation. These techniques provides near-optimal solutions with reduced computational complexity, making them suitable for complex optical network scenario.

In centralized control architectures, a single intelligent agent manages global network decision. In contrast, distributed optical network require multiple agents to coordinate and interact.

In such cases, game-theoretic approaches have been successfully employed to model competitive and cooperative behaviors in hybrid RF/FSO networks and elastic optimal networks.

More recently, knowledge based reasoning and learning enabled planning techniques have been introduced to enhance decision making capabilities. These approaches allow optical network controllers to maintain knowledge bases containing information about network states, traffic patterns, and historical performance, enabling adaptive and predictive control strategies.

Cognitive optical networks and AI challenges:

Intelligent agents in optical networks can observe the effects of their actions, enabling them to plan and adopt to changing network conditions. This capability forms the foundation of cognitive optical networks, which are designed to perceive, learn, adapt and optimize their performance autonomously.

Three primary challenges arise when integrating intelligence into optical systems: handling uncertainty, decision-making, and learning.

1) *Uncertainty:* Uncertainty is inherent in optical networks, as network events are often unpredictable or only partially observable. Bayesian networks provide a probabilistic framework for modelling such uncertainties, while Hidden Markov Models (HMMs) and Kalman filters enable agents to make predictions and manage temporal dynamics effectively.

2) *Decision-making:* Decision-making involves selecting actions that maximize expected utility. In realistic and uncertain environments, agents commonly employ Markov Decision Processes (MDPs) to model sequential decision problems and derive policies that guide optimal behavior.

3) *Learning:* Learning enables agents to adapt and improve over time, which is essential in dynamic optical networks where static, pre-programmed solutions are insufficient. AI agents leverage statistical and machine learning techniques to learn from monitoring data and operational feedback, enabling continuous performance optimization [11].

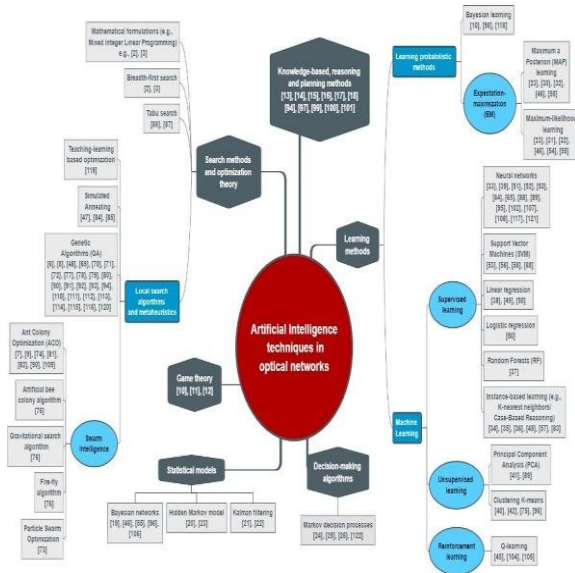


Fig. 3-AI Techniques in Optical Networks [11]

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VII. AI FOR PHOTONICS

Artificial Intelligence has emerged as a powerful tool in photonics, significantly enhancing the precision and efficiency of both forward modelling and inverse design. Complex optical phenomena including holography, quantum photonic experiments, and computational imaging, can be analyzed more efficiently using neural networks that rapidly map optical parameters to physical responses [13].

In inverse design, AI optimizes optical systems for imaging and communication applications and contributes to the development of intelligent metasurfaces and quantum photonic devices. Despite the advancements, challenges remain, particularly regarding the need for large, high-quality datasets and effective management of high-dimensional optical fields. To address these issues, back propagation-free and physics-aware training methods have been proposed offering improved robustness and interpretability[13].

VIII. PHOTONICS FOR AI

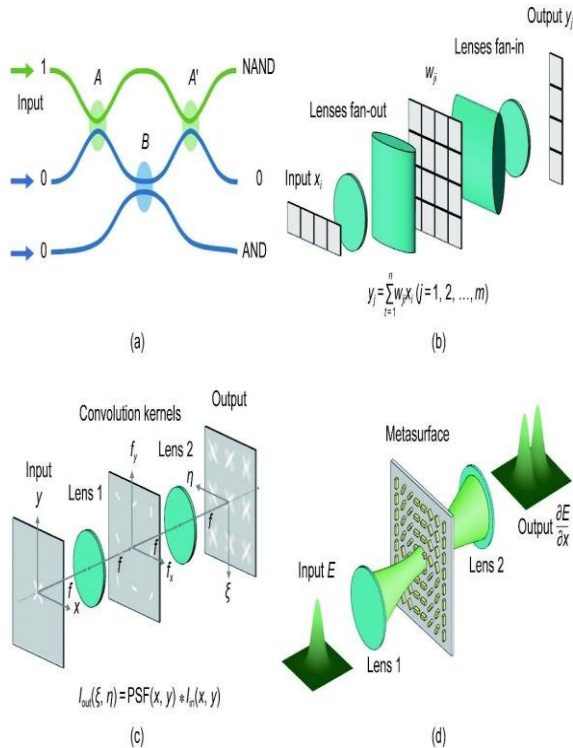
Photonics and Artificial Intelligence (AI) mutually benefit from one another.

While AI enables intelligent control, optimization, and design of photonic systems, the rapid advancement of AI technologies also introduces significant computational challenges, particularly the need for substantial processing power for large scale linear algebra operations and the associated high energy consumption. Developing photonics as a computing platform for AI acceleration has therefore emerged as a highly promising research direction to overcome this bottlenecks.

Photonic computing approaches can generally be classified into two categories: Digital optical computing and analog optical computing. Digital optical computing includes optical logic operations, optical logic operations, optical transistors, and logic devices, which operate using principles analogous to electronics digital computers. Considerable progress has made in demonstrating macro scale, micro scale, and moonscape optical system as potential candidates for optical logic gates implementations. These system are particularly attractive for specialized applications such as optical signal processing in fiber-optic communications, optical data storage, and large-scale optical quantum computing.

In contrast, analog optical computing exploits the inherent physical properties of light, including amplitude, phase, polarization and light-matter interactions, to perform mathematical operations without the need for additional multiplier proposed by Goodman in 1978. In this approach, a vector array of light sources is duplicated using lenses and multiplied by a matrix encoded onto a spatial light modulator (SLM). After multiplication, the optical signals are spatially integrated, with each detector element collecting contributions from a row of the SLM, thereby implementing a Linear multiply-and-accumulate operation. This model forms the basis for many optical computing architectures relevant to AI workloads.

The well-known 4f optical system, where ‘f’ denotes the focal length of the lenses, performs a cascade of two Fourier transforms and leverages the convolution theorem to realize matrix multiplication and convolution operations. These operations are fundamental to information processing and form the computational core of modern neural networks [54][55]. Furthermore, optical differential operations can be realized using implementation of tasks such as edge detection in image processing applications [13].



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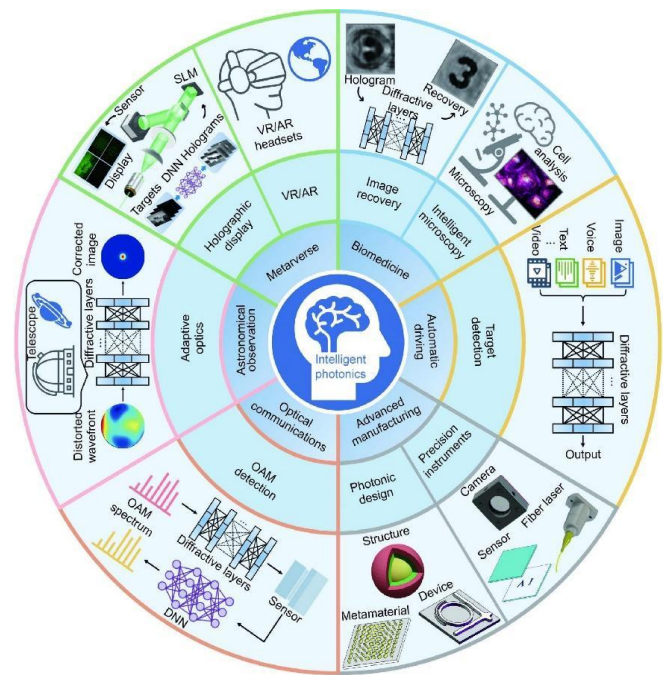
Fig. 4: Manipulating photons to perform mathematical calculations. (a) Optical implementation of energy-free logical gates to realize AND and NAND Boolean functions. (b) Configuration for optical vector-matrix multiplication. (c) A $4f$ optical system for convolution operations. (d) A first-order spatial differentiator based on metasurfaces[13]

Applications of intelligent photonics:

AI demonstrates strong potential for addressing complex scientific and engineering challenges, particularly due to the availability of large datasets, advances in massively parallel computing hardware, and the increasing integration of intelligent algorithms with photonic systems.

The integration of photonics with multilayer neural networks enables the extraction and identification of essential features from complex optical data. Recent advances in AI are driving a paradigm shift in physics and optical engineering, where photonic components are increasingly incorporated into AI models to address computationally intensive tasks in a timely and energy-efficient manner.

Intelligent photonics represents an interdisciplinary research area at the convergence of Physics, engineering and computer science. In parallel with significant progress in deep learning algorithms and photonic technologies, intelligent photonics has been widely applied across diverse domains. Representative driving, advanced manufacturing, optical communications, and astronomical observation. An overview of intelligent photonics-related applications is illustrated in Fig.5 .



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Fig. 5 : Intelligent photonics-related applications in diverse fields, including the metaverse, biomedicine, automatic driving, advanced manufacturing, optical communications, and astronomical observation.

IX. PHOTONIC INTEGRATED CIRCUITS AND META SURFACES

Photonics is undergoing a major transformation toward extreme miniaturization and enhanced performance. Foundational studies of diffraction, refraction, and interference have established the basis for modern Nano photonic system and optical computing architectures.

Among these developments, metasurfaces-ultrathin photonic structures composed of sub-wavelength elements-enables precise manipulation of light by controlling its phase, amplitude, and polarization across a surface.

Enabled by advanced semiconductor fabrication techniques, metasurface can be manufactured in a single lithographic step. By carefully tuning the size, shape and arrangement of their constituent meta-atoms, these structures can realize complex optical functionalities with significantly reduced footprints compared to conventional optical components.

As a result, metasurfaces can reduce the size of imaging and spectroscopy systems by up to several orders of magnitude while simultaneously capturing rich multidimensional optical information, including phase, polarization and wavelength.

This combination of compactness and information richness positions metasurfaces as a key enabler of next-generation, AI-driven vision and sensing systems [8].

In parallel, the integration of nanophotonics with machine learning has gained substantial momentum. Machine Learning techniques were initially applied to inverse photonic design, computational microscopy, and optical sensing, where they significantly reduced design time and improved performance.

More recently, photonic neural network(PNNs)-computational system that utilize light for information processing-have emerged as promising alternative to conventional electronic architectures, offering significantly higher processing speeds and improved energy efficiency. Their inherent capability to directly process optical signals makes them particularly suitable for intelligent, edge-level sensing and computing applications.

Despite these advantages, several critical challenges remain, including limitations in accuracy, generalization capability, configurability, and seamless integration with electronic hardware. Recent publication trends indicate increasing research momentum in metasurfaces, on-chip photonics, and diffractive neural network driven by the rapidly growing models. Consequently, optical neural networks are increasingly recognized as a visible pathway for overcoming fundamental speed and energy-efficiently constraints in next-generation computing systems [10].

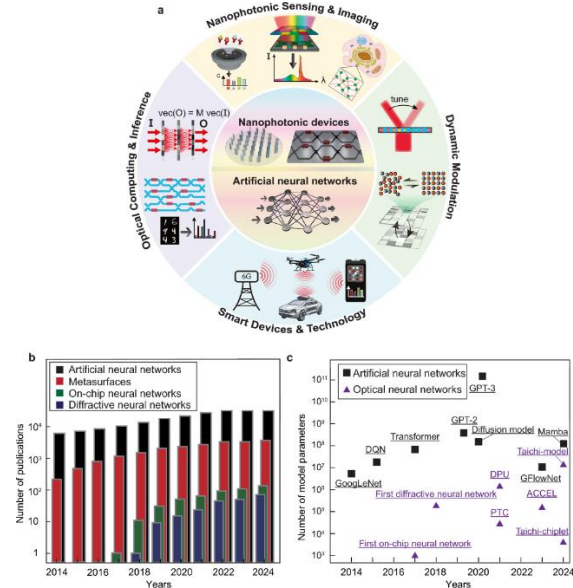


Fig. 6: Overview and emerging trends in intelligent photonics integration of A) Schematic illustrating applications enabled by the integration of nanophotonics and machine learning including computational sensing, imaging, optical computing and smart autonomous systems. B) Statistical distribution of publications in relevant fields over the past decade and c) comparison of state-of-the-art model sizes for digital artificial neural networks and optical neural networks[8]

<https://elight.springeropen.com/articles/10.1186/s43593-025-00085-x/figures/2>

X. AI AND MACHINE LEARNING: BROAD-BASED PHOTONICS APPLICATIONS [3]:

1. Design and simulation: Accelerated exploration of high-dimensional parameter spaces, enabling inverse design, and optimization of complex multi-component photonic systems [3].
2. Manufacturing and fabrication: Real-time process monitoring, predictive maintenance, quality control, and robotic automation [3].
3. Characterization and testing: Automated analysis of optical properties, defect detection, and high-throughput precision evaluation, metrology[3].
4. System control and optimization: Implementation of Adaptive optics, intelligent feedback loops, and self-calibrating systems [3].

5. Data analysis and discovery: Identification of patterns and trends in large-scale experimental or simulation datasets, facilitating accelerated discovery of novel materials and physical phenomena [3].

XI. CHALLENGES

Despite significant progress, several challenges hinder the widespread deployment of intelligent photonic systems. Scalability, Fabrication tolerances, and robustness to noise remain critical limitations, particularly for large scale optical neural network.

For a system-level perspective, emerging applications domain such as sixth-generation (6G) wireless communications impose stringent requirements on latency, bandwidth, and energy efficiency.

In this context, photonic computing and AI-assisted signal processing are considered promising enablers for high-capacity multicast and broadcast transmission, massive internet of Things (IOT) connectivity, and extended to play a critical role in realizing globally accessible 6G services by extending mobile coverage beyond terrestrial infrastructure.

Thus, non-terrestrial network (NTN) have the potential to overcome the coverage limitations of conventional terrestrial network(TNs). This paper examines how the distinctive feature of NTN can be effectively exploited to support multicast services in sixth generation (6G) communication system.

Furthermore, In alignment with the evolution of 6G towards software defined and virtualized architectures, the potential of a softwarization paradigm within heterogeneous TN/NTN networks is evaluated for efficient multicast service delivery[12].

XII. CONCLUSION

Artificial Intelligence(AI) and Machine Learning(ML) become integral to modern technological development, and their relevance expected to increase further in the near future.

Beyond their widespread impact on daily life, AI and ML have demonstrated significant potential in the fields of optics and photonics. In particular, data-driven approaches enable rapid analysis of large datasets and efficient identification of optimal design configuration, thereby substantially reducing the time and computational cost required for the development of advanced optical and photonic systems.

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