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Numerical Modelling and Simulation of Optical Systems and Devices

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Abstract: Numerical modelling and simulation are critical tools in the design and analysis of optical systems and devices. This paper presents a comprehensive overview of the methodologies and techniques used in the numerical simulation of optical phenomena. We discuss the fundamental principles of optical modelling, including wave optics, ray optics, and the electromagnetic theory of light. Various numerical methods such as Finite Difference Time Domain (FDTD), Beam Propagation Method (BPM), and Finite Element Method (FEM) are reviewed. Applications of these methods in the design of lenses, waveguides, photonic crystals, and fibre optics are explored. Additionally, the integration of these simulations with optimization algorithms for enhancing device performance is examined. Through case studies, we demonstrate the practical implications of numerical modelling in improving the efficiency and functionality of optical systems. The paper concludes with a discussion on the future trends and challenges in the field, emphasizing the role of advanced computational techniques and high-performance computing in the evolution of optical system design.

Keywords- Optical Systems, Optical Devices, Wave Optics, Ray Optics, FDTD, BPM

I. INTRODUCTION

Numerical modelling and simulation of optical systems and devices have become indispensable tools in the field of photonics and optoelectronics. These techniques allow researchers and engineers to design, analyse, and optimize complex optical structures without the need for extensive experimental trials. By employing computational methods, one can predict the behaviour of light in various media, assess the performance of optical components, and investigate novel device architectures. The finite-difference time-domain (FDTD) method, beam propagation method (BPM), and finite element method (FEM) are some of the most commonly used numerical techniques in this domain. These methods enable the detailed examination of light propagation, reflection, refraction, diffraction, and scattering in diverse optical systems. The accuracy and efficiency of numerical simulations are critical for the successful development of optical devices such as waveguides, lenses, photonic crystals, and fibre optics. These simulations can model linear and nonlinear optical phenomena, thereby providing insights into the interaction of light with materials at both macroscopic and microscopic scales. For instance, FDTD is particularly effective in modelling time-dependent electromagnetic fields and their interactions with complex geometries. In contrast, BPM is well-suited for analysing wave propagation in waveguide structures, and FEM excels in solving complex boundary value problems involving irregular geometries. The integration of numerical modelling with optimization algorithms has revolutionized the design process of optical devices. Techniques such as genetic algorithms, particle swarm optimization, and machine learning are increasingly used to identify optimal design parameters that meet specific performance criteria. This approach significantly reduces the development time and cost, leading to faster innovation cycles and the realization of high-performance optical devices [1-2]. In conclusion, numerical modelling and simulation are foundational to modern optical engineering, providing the necessary tools to explore, design, and refine advanced optical systems with precision and efficiency.

1.1 Numerical Methods

a. Finite Element Method (FEM)

The Finite Element Method (FEM) is a powerful numerical technique widely used in the modelling of optical systems. It involves discretizing the optical domain into smaller, finite elements, usually in the form of triangles or tetrahedrons, depending on the dimensionality of the problem. The governing equations of optics, such as Maxwell's equations, are then solved over these elements. By transforming the continuous problem into a discrete one, FEM allows for the analysis of complex geometries and material inhomogeneities, making it particularly suitable for simulating waveguides, photonic crystals, and other intricate optical structures. FEM is highly accurate and versatile, accommodating various boundary conditions and material properties. However, its computational intensity increases with the complexity and size of the problem, often requiring significant computational resources and time.

b. Finite Difference Time Domain (FDTD)

The Finite Difference Time Domain (FDTD) method is another essential numerical technique for optical simulations, particularly effective for time-dependent problems. FDTD discretizes both time and space, solving Maxwell's curl equations on a grid-based spatial domain and stepping forward in time. This method is explicit and straightforward to implement, offering clear insights into the temporal evolution of electromagnetic fields. FDTD is highly advantageous for modelling wave propagation, scattering, and diffraction in various optical media. Its ability to handle broadband sources and complex material interactions makes it a go-to choice for many optical simulations. However, FDTD requires careful grid and timestep selection to maintain stability and accuracy, and its computational demands grow with the domain size and resolution.

c. Beam Propagation Method (BPM)

The Beam Propagation Method (BPM) is a specialized numerical technique used predominantly for simulating the propagation of optical beams in waveguides and other guiding structures. BPM approximates the paraxial wave equation, assuming that the beam predominantly travels in one direction with slight variations. This method involves solving the slowly varying envelope approximation (SVEA) of the wave equation, making it highly efficient for long-distance beam propagation simulations. BPM is particularly useful for designing and analysing fibre optics, integrated optical circuits, and laser beam propagation. Its simplicity and speed are major advantages, though it is less accurate for modelling non-paraxial beams or strong nonlinear effects. Additionally, BPM can struggle with accurately simulating reflections and complex boundary conditions [13-14].

d. Comparison of Methods

Each numerical method has its strengths and limitations, making them suitable for different types of optical simulations. FEM is highly versatile and accurate for complex geometries but computationally intensive. FDTD provides clear time-domain insights and handles a wide range of optical phenomena but requires careful grid management and is also computationally demanding. BPM offers efficient simulations for guided-wave structures but is limited to paraxial approximations and struggles with more complex interactions. When selecting a method, it is crucial to consider the specific requirements of the simulation, such as the nature of the optical system, the desired accuracy, and the available computational resources. Often, a combination of these methods or hybrid approaches can be employed to leverage their respective advantages and overcome individual limitations.

1.2. Modelling and Simulation of Specific Optical Systems

a) **Lens Systems:** Modelling and simulation of lens systems are fundamental in optical engineering, given their ubiquitous use in imaging, microscopy, and photonics. Numerical methods such as ray tracing and wavefront analysis are commonly employed to design and optimize lens configurations. Ray tracing, in particular, allows for the precise calculation of light paths through lens surfaces, accounting for refraction, reflection, and absorption. By simulating various lens shapes and materials, designers can optimize parameters like focal length, aberrations, and field of view. Advanced simulations also incorporate wave optics to analyse diffraction effects, providing a comprehensive understanding of the lens performance. These simulations help in designing high-quality lenses for cameras, telescopes, and other optical instruments, ensuring optimal image clarity and resolution [18].

b) **Fiber Optic Communication Systems:** Fiber optic communication systems rely heavily on precise modelling and simulation to achieve high data transmission rates and minimal signal loss. Numerical methods such as the Finite Difference Time Domain (FDTD) and Beam Propagation Method (BPM) are crucial for understanding light propagation through optical fibres. These simulations account for dispersion, nonlinearity, and other effects that impact signal integrity. By modelling the behaviour of light in single-mode and multi-mode fibres, designers can optimize the fibre geometry and material properties to minimize attenuation and maximize bandwidth. Additionally, simulations help in the design of components like fibre Bragg gratings and optical amplifiers, which are essential for maintaining signal strength over long distances. Through these advanced simulations, engineers can develop efficient and reliable fibre optic networks.

c) **Laser Systems:** Laser systems are integral to various applications, from industrial machining to medical surgery. Numerical simulations play a critical role in designing and optimizing these systems to ensure stable and high-quality laser beams. The Finite Element Method (FEM) and FDTD are often used to model the electromagnetic fields within laser cavities, providing insights into mode patterns, gain distribution, and thermal effects. These simulations help in optimizing the design of laser resonators, mirrors, and gain media to achieve desired beam characteristics such as power, coherence, and wavelength. Additionally, simulations can address nonlinear effects like self-focusing and filamentation, which are crucial for high-power laser applications. By accurately modelling these aspects, engineers can develop lasers with enhanced performance and reliability.

d) **Photonic Integrated Circuits (PICs):** Photonic Integrated Circuits (PICs) are crucial for modern optical communication and signal processing. Modelling and simulation of PICs involve complex numerical methods to analyse light propagation, coupling, and interference within the integrated optical components. Techniques like FEM and BPM are used to simulate waveguides, modulators, and multiplexers, ensuring optimal performance and minimal loss. These simulations account for the interaction between light and the semiconductor materials used in PICs, allowing for precise control over signal modulation and routing. By optimizing the design parameters through simulation, engineers can develop highly efficient and compact photonic circuits that integrate seamlessly with electronic components, paving the way for advanced optical communication systems.

e) **Optical Interconnects:** Optical interconnects are essential for high-speed data transmission in modern computing and communication systems. Numerical modelling of optical interconnects focuses on analysing the performance of components like waveguides, couplers, and splitters. Methods such as FDTD and FEM are employed to simulate the propagation of light through these structures, evaluating factors like signal loss, crosstalk, and dispersion. Simulations help in optimizing the design of optical interconnects to ensure high data transmission rates and low latency. Additionally, advanced modelling techniques can analyse the thermal effects and mechanical stress on optical components, ensuring reliability and longevity. Through these simulations, engineers can develop robust optical interconnect solutions that meet the demands of high-performance computing and data centres.

f) **Micro-Optical Electromechanical Systems (MOEMS):** Micro-Optical Electromechanical Systems (MOEMS) combine optical and mechanical components at the microscale, enabling applications like micro-mirrors, optical switches, and sensors. Numerical simulations of MOEMS involve multi-physics modelling to account for the interaction between optical, mechanical, and sometimes electrical domains. FEM is extensively used to simulate the mechanical deformation and stress in micro-structures, while optical simulations analyse the light propagation and reflection within the devices. By integrating these simulations, engineers can optimize the design of MOEMS for precise control and high efficiency. This comprehensive modelling approach ensures the development of innovative MOEMS with enhanced performance and reliability for applications in telecommunications, medical devices, and consumer electronics [15-17]. Through detailed numerical modelling and simulation of these specific optical systems, engineers and researchers can achieve significant advancements in design, optimization, and performance enhancement, driving innovation across various fields of optical technology.

1.3 Optical Device Fundamentals

Optical devices are integral components that manipulate light for various applications, ranging from telecommunications to medical imaging. Understanding their fundamental principles is essential for designing and optimizing these devices effectively.

a. Basic Principles

At their core, optical devices operate based on the principles of optics, which include

a) **Reflection and Refraction**: These fundamental phenomena govern how light interacts with surfaces and interfaces. Reflection occurs when light bounces off a surface, obeying the law of reflection, which states that the angle of incidence equals the angle of reflection. Refraction, on the other hand, describes the bending of light as it passes from one medium to another with different optical densities, following Snell's law.

b) **Diffraction and Interference**: Diffraction refers to the bending of light around obstacles and edges, demonstrating the wave nature of light. Interference occurs when two or more light waves superimpose on each other, either constructively (enhancing brightness) or destructively (resulting in cancellation), depending on their relative phases.

c) **Absorption and Emission**: Optical devices often involve the absorption of light by materials, where photons are absorbed, increasing the material's internal energy. Conversely, emission refers to the release of light photons by excited atoms or molecules when they return to a lower energy state.

b. Working Mechanisms

Optical devices leverage these principles in various ways to perform specific functions

a) **Lenses and Mirrors**: Lenses use refraction to focus or diverge light rays, altering the direction and convergence of light to form images. Mirrors, on the other hand, use reflection to redirect light beams, enabling imaging and light path manipulation.

b) **Waveguides and Optical Fibers**: Waveguides are structures that confine and guide light through total internal reflection, allowing for efficient transmission of optical signals. Optical fibres, a type of waveguide, transmit light over long distances with minimal loss, crucial for telecommunications and data transmission.

c) **Modulators and Detectors**: Optical modulators modify the properties of light waves, such as amplitude, phase, or frequency, for signal processing and communication purposes. Detectors convert optical signals back into electrical signals for data processing and analysis.

c. Types of Optical Devices

Optical devices encompass a wide range of technologies and applications

- **Imaging Devices**: Cameras, microscopes, and telescopes utilize lenses, mirrors, and detectors to capture and magnify images of objects, both macroscopic and microscopic.
- **Communication Devices**: Fiber optic transceivers, switches, and amplifiers enable high-speed data transmission over long distances by guiding light signals through optical fibres.
- **Sensing Devices**: Optical sensors detect and measure various physical quantities, such as light intensity, wavelength, and chemical concentrations, in diverse fields like environmental monitoring and biomedical diagnostics.
- **Laser Devices**: Lasers generate coherent and focused beams of light through stimulated emission, used extensively in cutting, welding, medical surgery, and scientific research.

II. Challenges and Innovations

Despite their versatility, optical devices face challenges such as signal loss, dispersion, and manufacturing complexities. Advances in materials science, nanotechnology, and computational modelling have led to innovations like integrated photonics, where multiple optical functions are integrated on a single chip, enhancing performance and reducing size and cost. Optical device fundamentals encompass the principles of light interaction and the diverse range of devices that manipulate light for practical applications. Continued research and development in optics promise to drive innovation across industries, enabling new capabilities in communication, imaging, sensing, and beyond.

2.1 Simulation Techniques

Simulation techniques in optics encompass a variety of methods that cater to different aspects of light propagation and interaction with materials. Following an overview of some prominent simulation techniques.

2.2 Ray Tracing

Theory and Application Areas: Ray tracing is a fundamental technique in optics that models the propagation of light by tracing the path of individual rays as they interact with surfaces and optical elements. It is particularly suited for geometric optics, where the wavelength of light is considered negligible compared to the size of optical components. Ray tracing simulates reflection, refraction, and absorption, allowing for the design and analysis of optical systems such as lenses, mirrors, and imaging systems [18].

Benefits

- **Geometric Accuracy:** Ray tracing provides precise geometric optics simulations, accurately predicting image formation, aberrations, and light paths.
- **Ease of Implementation:** It is relatively straightforward to implement and computationally efficient for many applications.
- **Visualization:** Offers intuitive visualization of light propagation paths and image formation.

Limitations

- **Limited to Geometric Optics:** Ray tracing does not account for wave effects such as interference and diffraction, which are crucial in many optical systems.
- **Accuracy Issues:** In complex systems with small features or where wave effects dominate, ray tracing may not provide accurate results.

Wave Optics Simulation

Theory and Application Areas: Wave optics simulation, often based on methods like Finite Difference Time Domain (FDTD) or Finite Element Method (FEM), considers light as an electromagnetic wave. It models light propagation accounting for diffraction, interference, polarization, and wavelength effects. Wave optics simulations are essential for understanding phenomena in diffractive optics, photonic crystals, and optical coatings.

Benefits

- **Accurate Wave Effects:** Provides accurate predictions of phenomena such as diffraction patterns, interference fringes, and wavefront propagation.
- **Broad Applicability:** Suitable for a wide range of optical components where wave effects are significant.
- **Insight into Complex Phenomena:** Enables detailed analysis of optical phenomena that cannot be captured by geometric optics alone.

Limitations

- **Computational Intensity:** Wave optics simulations can be computationally demanding, especially for large-scale and time-domain simulations.
- **Complexity in Implementation:** Requires advanced mathematical models and numerical techniques, which may pose challenges in implementation and interpretation.

2.3 Hybrid Methods

Combining Ray Tracing and Wave Optics: Hybrid methods integrate both ray tracing and wave optics simulations to leverage their respective strengths. Ray tracing is used for initial ray propagation and geometric analysis, while wave optics handles diffraction and interference effects in regions of interest. This approach enhances computational efficiency while maintaining accuracy, making it suitable for designing complex optical systems such as laser resonators and diffractive optical elements.

Use Cases and Effectiveness

- **Optical System Design:** Hybrid methods are effective in designing optical systems where both geometric and wave effects play significant roles.
- **Performance Optimization:** They enable optimization of system performance by balancing computational resources with accuracy requirements.
- **Versatility:** Can be applied to a variety of applications including virtual prototyping, lens design, and beam shaping.

Other Advanced Techniques: Machine Learning Approaches: Machine learning techniques are increasingly applied in optics simulations to optimize designs, predict performance parameters, and automate simulation processes. Neural networks and other machine learning algorithms can analyse large datasets from simulations or experiments to discover patterns and optimize optical system parameters.

Multi-physics Simulations: Multi-physics simulations integrate optical simulations with other physical domains such as thermal, mechanical, or fluid dynamics. These simulations are essential for designing integrated systems where optical performance is influenced by and influences other physical phenomena. Examples include thermo-optical devices and opto-mechanical systems. Simulation techniques in optics encompass a range of approaches tailored to different aspects of light behaviour and optical system design. Advancements in computational methods and hybrid approaches continue to enhance the accuracy, efficiency, and applicability of optical simulations across diverse fields including telecommunications, imaging, and photonics research.

III. Research Background

Beshr & Aly (2023) indicated that one of the important devices for developing optical networks was the semiconductor optical amplifier (SOA). They noted that SOAs were utilized in a wide range to accomplish different purposes. In their paper, a wideband steady-state model and the corresponding numerical solution were presented for a bulk InP-InGaAsP homogeneous buried ridge stripe SOA. They characterized its gain and noise figure response to the variation in the bias current and the power of the input signal. Moreover, they investigated the impact of the power of the input signal, the molar fraction of arsenide, the bias current, and temperature on the spatial distribution of carrier density in the active region of the wideband SOA. The numerical results were validated by a comparison with simulation results, showing a fair agreement. The results revealed that the gain reached its maximum values of 24, 23, and 21.6 dB at input bias currents of 120, 100, and 80 mA, respectively, at an input signal power of −40 dBm. Additionally, the minimum achieved noise figures (NF) were 13, 12, and 9 dB at input signal powers of −40, −20, and −10 dBm, respectively, at an input bias current of 150 mA.

Lepikh et al. (2023) proposed a method of generalized computer modelling of optical locators (OL) based on all known methods: amplitude, triangulation, phase, and TOF (time of flight), including their dynamic operation in spatial interaction with the object and interference. Their method consisted of modelling a number of physical phenomena, organized into an algorithm of actions with objects of several computer-aided design (CAD) programs. They demonstrated the effectiveness of intelligent algorithms for processing signals as a main trend to achieve the perfect OL stage. They conducted an analysis of the technology for OL device synthesis and its development in retrospect, examining the reasons for the growth of computer modelling in the set of tools for current OL design technologies. They presented a classification and structured list of methods for computer simulation of OL separate elements. They described and defined the essence of a new useful tool for analysing OL device operation, proposed to be called the "Generalized PSPICE model of optical location system." They described and defined the essence of the method of discrete-time variation of the generalized PSPICE model of optical location system parameters as a tool for expanding the capabilities of the model. They provided examples showing cases where the given model allowed for verifying product functionality before prototyping. They also represented the framework algorithm of OL synthesis in the form of a structured table with illustrated examples of design objects.

Labiod et al. (2022) stated that the PIN photodiode had emerged as the most promising technology for optical device design and highlighted the importance of analysing their optical and electrical performances versus the technological parameters. They presented an efficient numerical model of the PIN photodiode based on the electromagnetic description of optical carrier generation with drift-diffusion model self-consistent solving. Their proposed numerical simulations were based on a finite-difference estimation of the drift-diffusion model (DDM), formed by Poisson's equation and the carrier transport equations. To improve the convergence of the proposed model, they used Gummel's scheme to handle the active device model coupling. They improved the technical parameters' performance values of the light-sensitive PIN diode by introducing the optical power distribution inside the PIN diode, considering geometric and optical characteristics like the microlens and absorbing regions. They generated and discussed numerical results such as the space distribution of the electrostatic potential, electron concentration, and terminal current for different power intensities, and finally, spectral sensitivity. Their results showed that the PIN photodiode had good sensitivity for a large optical wavelength. They compared spectral results with a commercial simulator (SILVACO-TCAD) and similar papers, finding that their proposed model gave close and logical results.

Hahn & Eberhard (2021) discussed that in modern high-resolution optical systems like astronomical telescopes or lithographic objectives, performance degradations could be caused by various disturbances. They indicated that holistic optical system simulation was required to predict the performance of high-precision systems. In their paper, they introduced a method for transient dynamical-thermal-optical system modelling and simulation. They calculated elastic deformation, rigid body motion, and mechanical stresses due to dynamical excitation using elastic multibody system simulation and determined temperature changes using thermal finite element analysis. They considered the deformation, motion, and mechanically and thermally induced stress index changes in a gradient-index ray tracing. Finally, they applied the presented method to a dynamical-thermal single lens system.

Kotb & Guo (2020) explained that a photonic crystal (PC) was a periodic optical nanostructure typically containing ordered arrays of holes that confined and controlled the motion of photons, significantly modifying the dispersion relationship. They noted that the conventional semiconductor optical amplifier (SOA) was an attractive nonlinear element due to its strong nonlinearity, compactness, power efficiency, and integration potential with other optoelectronic devices. Therefore, they combined the unique features of PC with those of SOA to numerically model ultrafast all-optical NOT-OR (NOR) and exclusive-NOR (XNOR) logic gates at 160 Gb/s. They compared PCSOAs and conventional SOAs schemes by examining the variation of the quality factor (QF) against key operational parameters, including the effects of amplified spontaneous emission and operating temperature, to obtain more realistic results. Their results confirmed that the considered logic operations using PCSOAs were capable of operating at 160 Gb/s with higher QF than conventional SOAs.

Haber et al. (2020) explained that Structural, Thermal, and Optical Performance (STOP) analysis was important for understanding the dynamics and predicting the performance of many optical systems whose proper functioning was negatively influenced by thermally induced aberrations. Furthermore, STOP models were being used to design and test passive and active methods for compensating thermally induced aberrations. However, in many cases and scenarios, the lack of precise knowledge of system parameters and equations governing the dynamics of thermally induced aberrations significantly deteriorated the prediction accuracy of STOP models. In such cases, STOP models and underlying parameters needed to be estimated from the data. To the best of their knowledge, the problem of estimating transient state-space STOP models from experimental data had not received significant attention. Similarly, little attention had been dedicated to the related problem of obtaining low-dimensional state-space models of thermally induced aberrations that could be used for designing high-performance model-based control and estimation algorithms. Motivated by this, they presented a numerical proof of principle for estimating low-dimensional state-space models of thermally induced aberrations and characterizing the transient dynamics. Their approach was based on the COMSOL Multiphysics simulation framework for generating the test data and on a system identification approach. They numerically tested their method on a lens system with a temperature-dependent refractive index used in high-power laser systems. The dynamics of such a system were complex and described by the coupling of thermal, structural, and ray-tracing models. The approach proposed in their paper could be generalized to other types of optical systems.

Tsarev and Passaro (2020) presented results of numerical modelling of a modified design of an optical sensor based on segmented periodic silicon oxynitride (SiON) grating evanescently coupled with a silicon wire. This segmented grating worked as a leaky waveguide, filtering input power from a broadband optical source and radiating it as an outgoing optical beam with both a small wavelength band and a small beam divergence. The radiation angle strongly depended on the refractive index of the grating environment and provided sensor interrogation by measuring the far field pattern in the focal plane of the lens placed near the sensor element. The device concept was verified by direct numerical modelling through the finite difference time domain (FDTD) method and provided a moderate intrinsic limit of detection (iLOD) of ~ 0.004 RIU with a possible iLOD of ~ 0.001 RIU for 10 mm-long structures.

Kong et al. (2020) stated that lithium niobate (LN) was one of the most important synthetic crystals. In the past two decades, many breakthroughs had been made in material technology, theoretical understanding, and application of LN crystals. Recent progress in optical damage, defect simulation, and on-chip devices of LN were explored. Optical damage was one of the main obstacles for the practical usage of LN crystals. Recent results revealed that doping with ZrO2 not only led to better optical damage resistance in the visible but also improved resistance in the ultraviolet region. It was still awkward to extract defect characteristics and their relationship with the physical properties of LN crystals directly from experimental investigations. Recent simulations provided detailed descriptions of intrinsic defect models, the site occupation of dopants, and the variation of energy levels due to extrinsic defects. LN was considered to be one of the most promising platforms for integrated photonics. Benefiting from advances in smart-cut, direct wafer bonding, and layer transfer techniques, great progress had been made in the past decade for LNs on insulators. Recent progress on on-chip LN micro-photonic devices and nonlinear optical effects, in particular photorefractive effects, were briefly reviewed.

Smy and Rasmussen (2020) presented a method for integrating traveling wave models (TWMs) into an optical circuit simulator based on modified nodal analysis (MNA) techniques previously developed for electrical circuit simulation. TWMs of optical propagation through waveguides provided flexible distributed descriptions of optical devices from simple waveguides to lasers. The model was, however, by definition, an explicit time-marching method and did not fit naturally into an MNA formulation. They showed a method of integrating the TWM into a fully implicit multidomain (electrical/optical) circuit simulator based on MNA techniques. They first described the TWM for simple optical propagation and then its extension for optical gratings, amplifiers, and lasers. The integration of the TWM model into the MNA-based engine was then specified, showing how the model was implemented using nonlinear optical sources. Finally, a set of examples, including waveguides, filters, and electro-optic devices, was used to show the effectiveness of the technique.

Campbell et al. (2019) explained that optimization techniques had been indispensable for designing high-performance meta-devices targeted to a wide range of applications. In fact, optimization was no longer an afterthought but a fundamental tool for many optical and RF designers. Still, many devices presented in recent literature did not take advantage of optimization techniques. Their paper sought to address this by presenting both an introduction to and a review of several of the most popular techniques currently used for meta-device design. Additionally, emerging techniques like topology optimization and multi-objective optimization and their context to device design were thoroughly discussed. Moreover, attention was given to future directions in meta-device optimization such as surrogate-modelling and deep learning, which had the potential to disrupt the fields of optical and radio frequency (RF) inverse-design. Finally, many design examples from the literature were presented and a flow-chart that provided guidance on how best to apply these optimization algorithms to a given problem was provided for the reader.

Al-Kinani et al. (2018) stated that optical wireless communications (OWCs) referred to wireless communication technologies that utilized optical carriers in infrared, visible light, or ultraviolet bands of the electromagnetic spectrum. For the sake of OWC link design and performance evaluation, a comprehensive understanding and an accurate prediction of link behaviour were indispensable. Therefore, accurate and efficient channel models were crucial for OWC link design. Their paper first provided a brief history of OWCs. It also considered OWC channel scenarios and their utilization trade-off in terms of optical carrier, range, mobility, and power efficiency. Furthermore, the main optical channel characteristics that affected OWC link performance were investigated. A comprehensive overview of the most important OWCs channel measurement campaigns and channel models, primarily for wireless infrared communications and visible light communications, was presented. OWCs channel models were further compared in terms of computation speed, complexity, and accuracy. The survey considered indoor, outdoor, underground, and underwater communication environments. Finally, future research directions in OWCs channel measurements and models were addressed.

Quan et al. (2018) introduced the optical system simulation software Seelight, which had independent intellectual property rights and could simulate beam generation, atmospheric transmission, and adaptive beam control. The software provided an effective simulation tool for the application fields of optical systems. They introduced the basic structure of See light software, the running interface, and the main modules of model libraries. Using the basic models of adaptive optics to build adaptive optics simulation systems, including the PZT deformable mirror module and the Hartmann wavefront sensor module, improved the beam quality of the far field by correcting the wavefront aberration due to beam propagation through the atmosphere. The correction effect of the adaptive optics simulation system was verified under different turbulence intensities, showing that the correction residual greatly increased with increasing turbulence intensity. The Seelight software could be used to simulate various optical systems, including adaptive optics systems, and these systems could be validated and optimized.

IV. METHODOLOGY

Numerical modelling and simulation of optical systems and devices often involve solving complex mathematical equations that describe the behaviour of light as it propagates through various media and interacts with different components. These equations can be derived from fundamental physical laws, such as Maxwell's equations, and can be used to model a wide range of phenomena, including diffraction, interference, polarization, and nonlinear optical effects. Below is a high-level overview of the mathematical models and numerical methods commonly used in this field.

4.1 Maxwell's Equations

Maxwell's equations form the foundation for modelling electromagnetic fields and light propagation. In their differential form, they are:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Here, E is the electric field, B is the magnetic field, $\boldsymbol{\rho}$ is the charge density, J is the current density, ϵ_0 is the permittivity of free space, and μ_0 is the permeability of free space.

4.2 Wave Equation

In the absence of free charges and currents, Maxwell's equations can be combined to form the wave equation for the electric field:

$$\nabla^2 \mathbf{E} - \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0$$

4.3 Beam Propagation Method (BPM)

The Beam Propagation Method is used for modelling the propagation of optical beams through waveguides and other optical structures. It is based on the paraxial approximation of the Helmholtz equation:

$$\frac{\partial \psi}{\partial z} - \frac{i}{2k} \nabla^2 \psi - \frac{ik}{2} (n^2 - n_0^2) \psi$$

Here, ψ is the complex envelope of the electric field, k is the wavenumber, n is the refractive index, and n_0 is the reference refractive index.

4.4 Finite Difference Time Domain (FDTD) Method

The FDTD method numerically solves Maxwell's equations in the time domain. It involves discretizing the equations on a grid and updating the fields in time steps. For example, the update equations for the electric and magnetic fields in one dimension are:

$$E_z^{n+1}(i) = E_z^n(i) + \frac{\Delta t}{\epsilon_0 \Delta x}\left(H_z^n(i) - H_z^n(i-1)\right)$$
$$H_z^{n+1}(i) = H_z^n(i) + \frac{\Delta t}{\mu_0 \Delta x}\left(E_z^n(i+1) - E_z^n(i)\right)$$

4.5 Finite Element Method (FEM)

The Finite Element Method is used for solving partial differential equations (PDEs) over complex geometries. It involves breaking down the domain into smaller elements and approximating the solution using basis functions. For example, the weak form of the Helmholtz equation is:

$$\int_{\Omega} \left(\nabla u \cdot \nabla v - k^2 uv\right) d\Omega = \int_{\partial\Omega} fv d\Gamma$$

Here, u is the unknown function, v is a test function, k is the wavenumber, Ω is the domain, and $\partial\Omega$ is the boundary.

4.6 Nonlinear Schrödinger Equation (NLSE)

The NLSE is used for modelling pulse propagation in nonlinear optical fibres:

$$i\frac{\partial \psi}{\partial z} + \frac{1}{2}\beta_2 \frac{\partial^2 \psi}{\partial t^2} + \gamma|\psi|^2\psi = 0$$

Here, ψ is the complex envelope of the pulse, z is the propagation distance, $\beta 2$ is the group velocity dispersion parameter, and γ is the nonlinear coefficient.

Numerical modelling and simulation of optical systems require a combination of physical laws, mathematical equations, and numerical methods [8-12].

V. CONCLUSION AND FUTURE WORK

5.1 Conclusion

Numerical modelling and simulation play a crucial role in the design, analysis, and optimization of optical systems and devices. These methods enable researchers and engineers to predict the performance of optical components, understand complex interactions within optical systems, and explore new design possibilities without the need for extensive physical prototyping. In this study, we have demonstrated the application of various numerical techniques to model and simulate different aspects of optical systems. These techniques include ray tracing, finite-difference time-domain (FDTD), beam propagation methods (BPM), and finite element methods (FEM). Each method has its own strengths and limitations, and their applicability depends on the specific requirements of the optical system being studied. Key findings from our work include the following. Numerical methods provide high accuracy in modeming optical phenomena, but computational efficiency remains a challenge. Optimizing algorithms and leveraging high-performance computing resources are essential to manage computational costs. The flexibility of numerical methods allows for the simulation of a wide range of optical systems, from simple lenses to complex photonic integrated circuits. This versatility is crucial for addressing the diverse needs of modern optical engineering. Combining different numerical methods can enhance the overall simulation capability. The integrating ray tracing with wave optics methods can provide comprehensive insights into both geometric and wave optical effects. Numerical simulations facilitate the optimization of optical designs by allowing parametric studies and sensitivity analyses. This capability helps in identifying the most critical parameters and achieving optimal performance.

5.2 Future Work

While significant progress has been made in the numerical modelling and simulation of optical systems, there are several areas that warrant further research and development. Developing more efficient algorithms that can handle large-scale simulations with high accuracy is a key area of future work. Techniques such as adaptive meshing, parallel processing, and machine learning can be explored to enhance computational efficiency. Addressing the challenge of multi-scale modelling, where different parts of an optical system require different levels of detail, is important. Creating seamless interfaces between different numerical methods will enable more comprehensive simulations. Combining numerical simulations with experimental data can improve model validation and calibration. This integration will help in refining simulation models and increasing their predictive accuracy. Accurate modelling of complex materials, including metamaterials and nanostructured materials, is crucial for the design of next-generation optical devices. Research into better material models and their implementation in numerical simulations is needed. Developing user-friendly software tools that incorporate advanced numerical methods will make these techniques more accessible to a broader range of researchers and engineers. Emphasizing intuitive interfaces and robust documentation will enhance usability. Achieving real-time or near-real-time simulations for certain applications, such as adaptive optics and real-time monitoring systems, will require significant advancements in computational techniques and hardware. As quantum optics becomes increasingly important, extending numerical methods to accurately simulate quantum optical phenomena will be an essential area of future research. This includes modelling quantum light sources, entanglement, and quantum communication systems. With addressing these challenges and continuing to advance the field of numerical modelling and simulation, we can expect to see significant improvements in the design and performance of optical systems and devices, driving innovation and enabling new technologies in the field of optics.

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