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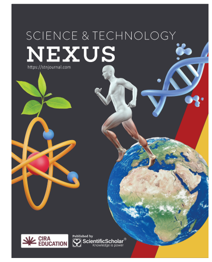

Review Article

From Light to Innovation: Exploring the Cutting-Edge Developments in Photonic Devices and Applications

Lina M. Shaker[1], PhD; Ahmed A. Al-Amiery[1], PhD; Wan R. Isahak[2], PhD

[1]Al-Ayen Scientific Research Center, Al-Ayen Iraqi University, AUIQ, An Nasiriyah, Thi Qar, Iraq, [2]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia, Bangi, Selangor, Malaysia.

***Corresponding author:**
Dr. Ahmed A. Al-Amiery, Al-Ayen Scientific Research Center, Al-Ayen Iraqi University, AUIQ, An Nasiriyah, Thi Qar, Iraq

dr.ahmed1975@gmail.com

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ABSTRACT

The rapid progress in the field of optics and photonics has paved the way for groundbreaking innovations across various sectors. This review paper delves into the cutting-edge developments in photonic devices and applications that are revolutionizing industries such as telecommunications, information processing, imaging, and energy. By exploring advancements in quantum optics, integrated photonics, optical materials, and photonic devices, this paper highlights the immense potential of harnessing light for technological innovation. It critically analyses the state-of-the-art research, identifies key challenges, and presents future directions in the field. This comprehensive review aims to inspire researchers, engineers, and policymakers to leverage the power of light for transformative advancements in the modern era.

Keywords: Imaging, Optics, Photonics, Photonic devices, Quantum optics

1. INTRODUCTION

The field of optics may broadly be described as the manipulation of light from a fundamental perspective. Many consider optics to be the classical study of the behaviour and properties of light.[1] Photonics focuses on the generation of photons, detection of photons, and utilization of photons in various applications.[2-5] After a long history spanning centuries, the recent technological advancements and engineering applications have rapidly shifted optics and photonics to the forefront of industry.[6-9] Since optics and photonics found their way to revolutionize telecommunications, along with information processing, imaging, and energy, the controlled use of light has profited a great deal from high speed optical communication networks, ultra-precise imaging, energy-efficient lighting, and modern photonics devices.[10,11] More traditional research begins to take effect in wearable tech through optics and photonics, mostly in advanced contact lenses [Figure 1]. The optical-functionalized contact lens (CL) has become one of the most promising areas for research and development.[2] These smart contact lenses do not merely correct vision-they go on to include optical components and sensors to enhance functionality and enable real-time data/data monitoring. Contact lenses with microscale optical sensors, for instance, allow for the non-invasive and continuous monitoring of glucose levels in tears for patients affected by diabetes.[3] The augmented reality aspects of contact lenses can also map digital information to the wearer's field of view, opening other exciting possibilities for immersive experiences, medical diagnostics, and personalized displays.[4-6] In fact, the incorporation of optics and photonics into contact lenses may offer profound solutions in health care, sports, and

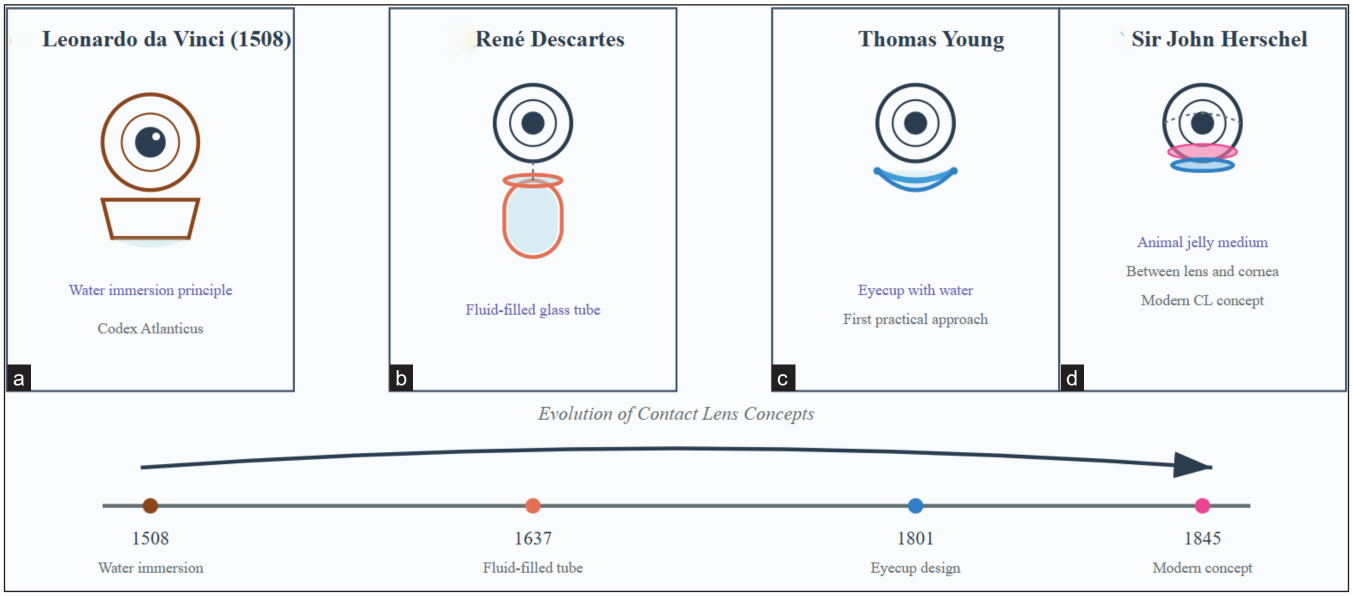

Figure 1: (a) A drawing by Leonardo da Vinci from his manuscript (1508). Leonardo da Vinci described the principles of contact lenses (CLs) in Codex Atlanticus. (b) Fluid-filled tube description as CL by René Descartes, (c) Eyecup design described by Thomas Young, and (d) Animal jelly sandwiched between the CL and cornea, as suggested by Sir Jon Herschel.

entertainment. By seamlessly integrating optical technologies with the ease and comfort of contact lenses, researchers and engineers are pushing the horizon further.[7,8] Consequently, these smart lenses can help in improving vision while also enabling a plethora of applications that were not given a second thought a few decades ago.[11,12] That is the ability of harnessing light properties which unleashed the alternate route of opportunity for the collaborative effort of researchers and engineers.[12]

The fusion of optics and photonics with wearable technology, like contact lenses, holds immense potential for the future. As demand for smaller and portable optical devices keeps increasing, the development of advanced contact lenses will become instrumental in determining the future of optics and its effect on various industries. With more research and technological advancements, contact lenses will reach an even higher degree of sophistication-a compelling pathway for innovation in optics, offering promising opportunities for future research and application. The photonic devices and their applications hold ground due to their potential of exploring technologies and introducing changes in multiple domains.[13] Photonic devices use all forms of light: from transmission to modulation, detection, and manipulation.[14] Compared with electronics, photonic elements exhibit anodized advantages of high data transfer rate, low power consumption, compactness, and improved performance.[15] In telecommunications, photonic devices find application through which optical fibres transmit data at a very fast speed over a very long distance and constitute the backbone of the global communication network.[16] For information processing, photonic devices make fast data processing possible and provide solutions for optical and quantum information processing, which may bring revolutionary improvements in computation and security.[17] Imaging is another area experiencing enhancements through photonics for high-resolution imaging techniques, such as confocal microscopy, optical coherence tomography, and fluorescence spectroscopy. This development in imaging has been a boon in the fields of medicine, biology, material science, and remote sensing.[18] Moreover, photonic devices have an important role in advancing renewable energy technologies. Photovoltaic devices convert solar energy into electricity; concentrated solar power systems utilize optics to capture and concentrate solar energy for power generation. These advances hold grave implications for Sustainable energy generation and the fight against climate change.[19] Hence the importance of photonic devices and their applications does not end with specific industries. They promote basic scientific studies, health service diagnostics and therapy, environment monitoring, and so forth. Photonic device and application advancements can bring about innovation with the future of the technology.[20] This review paper intends to explore the cutting-edge developments in photonic devices and their applications, with a focus on the latest advancements, challenges, and future directions. When the paper touches upon the exciting possibilities brought forward by optics and photonics, it envisions that researchers, engineers, and policymakers should be inspired to harness light for transformative innovation in modern times.

2. QUANTUM OPTICS: UNLOCKING THE POTENTIAL OF PHOTONS

2.1. Quantum mechanics and its role in quantum optics

Quantum mechanics, governing matter at the microscopic level, constitutes the major theoretical leg upon which quantum optics stand.[21] One must understand the laws of quantum mechanics to delve into photonic behaviour and its powers. This section will cover briefly fundamental quantum mechanics concepts and their bearing on quantum optics. Wave-particle duality, state superposition, entanglement, and randomness as manifestations of quantum phenomena will be among the topics discussed. Further discussions about the quantization of light, photon statistics, and light-matter interaction will pave the way for an in-depth study of quantum optics.[22] The conceptual framework and mathematical apparatus of quantum optics stem from quantum mechanics. The very idea of wave-particle duality that highlights the dual nature of photons is the one that can elucidate interference and the photoelectric effect. Superposition means photons exist in multiple incompatible states, non-classical behaviours vital for quantum computer and quantum cryptography technologies. While entanglement allows correlations between distant photons, investigators have never found a classical explanation for such correlations that is used in both quantum communication and teleportation. The quantization of light then makes us realize that electromagnetic fields consist of discrete quanta (photons), each with energy E=hν. This leads to the study of photon statistics, which distinguishes between classical and quantum sources of light. For instance, coherent sources like lasers follow Poissonian distributions, whereas true single-photon sources show sub-Poissonian behaviour, a hallmark of quantum light. Finally, the interaction between light and matter, such as in atomic transitions, reveals phenomena like Rabi oscillations and resonance fluorescence. These quantum-level interactions underpin many applications in quantum metrology and quantum information science.

2.2. Quantum communication and cryptography

Quantum communication represents a revolutionary approach to secure information exchange. By exploiting the principles of quantum mechanics, quantum communication protocols ensure that information transmission remains secure against eavesdropping and interception. Illustratively, QKD can allow secret keys to be distributed with unconditional security. This section provides the principles of quantum communication involving qubits, quantum entanglement, quantum teleportation, and quantum repeaters. Further in the section, we discuss the practical applications of quantum communication, the current status of quantum cryptography, and the problems encountered in scaling up quantum communication networks.[23,24] Figure 2 presents a comprehensive overview divided into six labelled components for clarity: (a) *Core Quantum Principles* – foundational quantum mechanical concepts such as qubit superposition, entanglement, measurement disturbance, and the no-cloning theorem. (b) *Quantum Key Distribution (QKD)* – secure key exchange protocols including BB84 and E91, along with

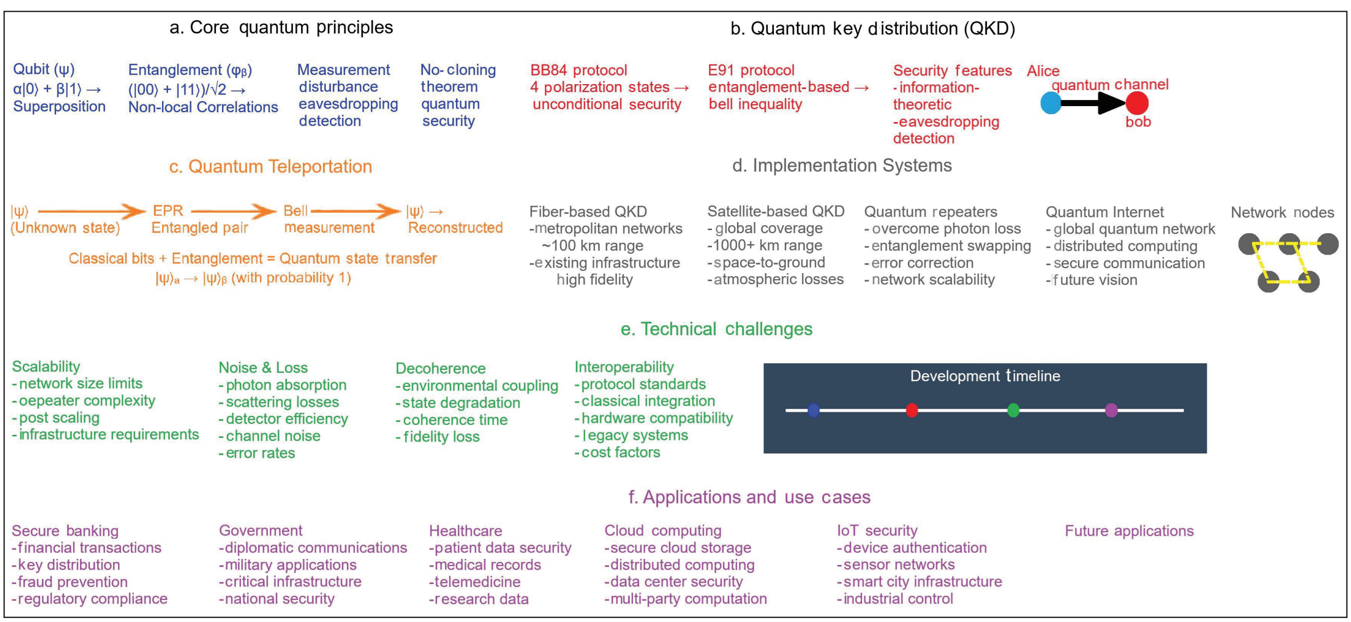

Figure 2: Architecture, protocols, and challenges in quantum communication and cryptography. (a) Core quantum principles; (b) Quantum key distribution (QKD); (c) Quantum teleportation; (d) Implementation systems; (e) Technical challenges; and (f) Applications and use cases.

security features like eavesdropping detection and quantum channel setup. (c) *Quantum Teleportation* – visualization of state transfer using EPR entanglement, Bell measurement, and classical communication. (d) *Implementation Systems* – real-world realizations such as fibre-based and satellite QKD, quantum repeaters, and the emerging quantum internet. (e) *Technical Challenges* – major challenges including scalability, noise, decoherence, and interoperability, along with a projected development timeline. (f) *Applications and Use Cases* – sectors benefiting from quantum communication, including finance, government, healthcare, cloud computing, IoT security, and future technologies.

3. INTEGRATED PHOTONICS: THE CONVERGENCE OF OPTICS AND ELECTRONICS

3.1. Fundamentals of integrated photonics

Integrated photonics is the name given to the interdisciplinary field that unites optics and electronics so that optics components and functionalities may be implemented on the same chip. This section will cover the fundamentals of integrated photonics, including waveguide basics, passive and active optical components, and light-matter interaction in integrated devices. Design principles, fabrication techniques, and material platforms will be discussed, possibly including photonic crystals, microresonators, and nanophotonic structures to gain a conceptual and a fairly technical understanding of the basics of the subject field.[25] Figure 3 presents the core concepts underlying the fundamentals of integrated photonics, organized into four labelled sections for clarity: (a) *Waveguides,* (b) *Passive and Active Components,* (c) *Light-Matter Interaction*, and (d) *Design and Fabrication*. Together, these four components provide a comprehensive visual framework for understanding how integrated photonics combines optical physics, device engineering, and fabrication technology to enable scalable, high-performance photonic systems.

3.2. Silicon photonics and its applications

As silicon photonics are compatible with standard semiconductor fabrication processes, this line emerged prominently in integrated photonics. This section will primarily consider silicon photonics, wherein its unique properties, including high refractive index, low propagation loss, and strong light-matter interaction, will be discussed. Thereafter, an application of silicon photonics from the viewpoint of data communication, optical interconnects, sensing, and biomedical applications will be discussed. Further advancements in hybrid integration, silicon modulators, and detectors will be discussed, offering a perspective on the current research and practical implementations within silicon photonics.[26]

3.3. Photonic integrated circuits for high-speed communication

Today's photonic integrated circuits have heralded a revolution in high-speed communication systems, thus providing compact, energy-efficient, and cheaper avenues to accomplish these modes. Consequently, this section will study PIC development for high-speed communication systems, including subjects such as on-chip lasers, modulators,

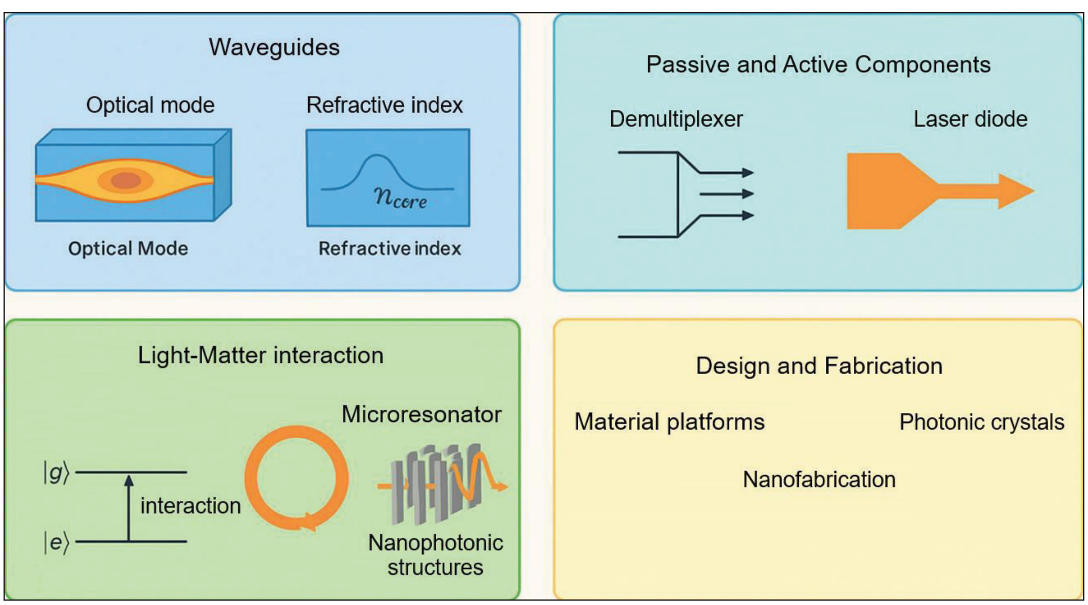

Figure 3: Core concepts in the fundamentals of integrated photonics.

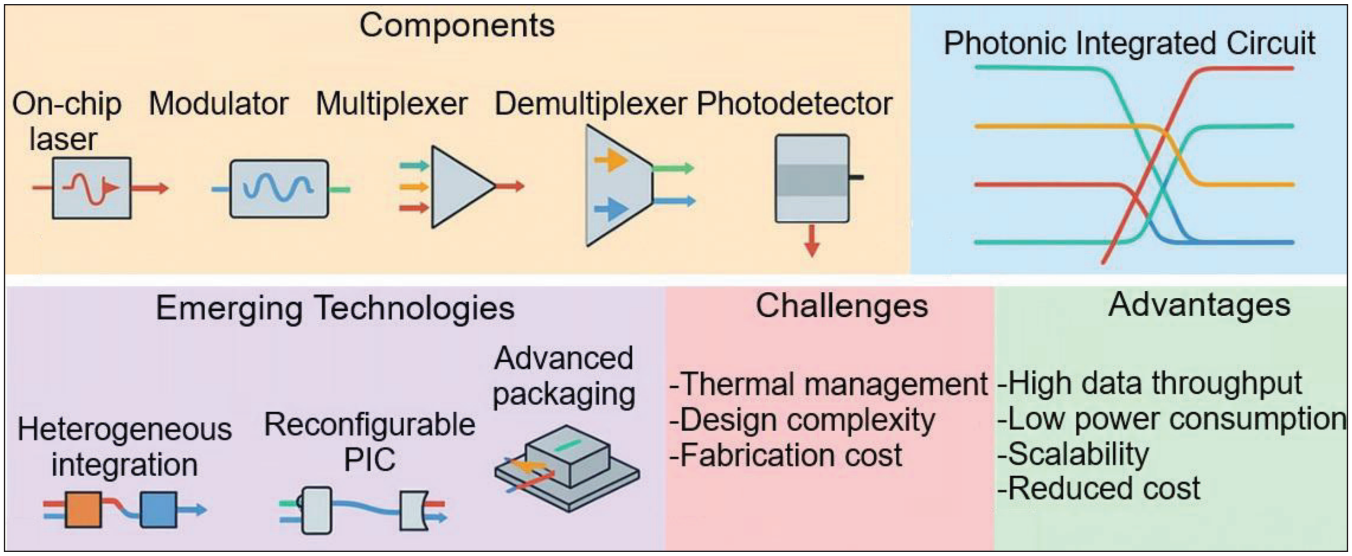

Figure 4: Photonic integrated circuits for high-speed communication: Architecture, benefits, and challenges.

detectors, multiplexers, and demultiplexers. Consideration of the integration of these elements on one single chip will ensue, as in enhanced performance, minimized power consumption, and scalability. Other relevant topics will be emerging technologies in PIC such as heterogeneous integration, reconfigurable PIC, and advanced packaging techniques. Challenges faced in PICs' design and fabrication will be highlighted, and their future prospects and applications[27] will be portrayed. Figure 4 provides a structured overview of photonic integrated circuits (PICs) tailored for high-speed communication systems, segmented into five key labelled areas: (a) *Components*, (b) *Advantages*, (c) *Photonic Integrated Circuit*, (d) *Emerging Technologies* and (e) *Challenges*.

Table 1: Types and examples of optical materials.

Optical material type	Examples
Crystalline materials	Quartz, Sapphire, Diamond, Potassium Dihydrogen Phosphate (KDP)
Glasses	Silica (SiO_2), Borosilicate, Soda-lime, Lead Glass
Semiconductors	Silicon (Si), Gallium Arsenide (GaAs), Indium Phosphide (InP)
Polymers	Poly(methyl methacrylate) (PMMA), Polycarbonate (PC), Polyimide
Nanomaterials	Quantum Dots, Carbon Nanotubes, Graphene, Nanoparticles

4. OPTICAL MATERIALS: EXPLORING NEW FRONTIERS

Table 1, presents an overview of different types of optical materials and their examples. The optical material plays a greater role in optics and photonics since it manipulates light for specific applications. Knowing the characteristics of various optical materials will help in designing new optical devices. The table encloses various categories of optical materials with their examples. As transparent materials capable of excellent light transmission, crystals like quartz and sapphire have an array of uses in optics. Glasses (comprising silica and borosilicate archetypes) are extremely desirable for their ease of fabrication and varying optical effects. Complementing these purposes, semiconductors such as silicon and gallium arsenide are put to use in optoelectronics. Polymers like poly(methyl methacrylate) (PMMA) or polycarbonate (PC) give added flexibility in numerous optical applications. Nanomaterials such as quantum dots, carbon nanotubes, graphene, and metal or nonmetal nanoparticles have unusual optical properties at the nanoscale. With an idea of the various optical materials and some of their specific properties, researchers and engineers can select the best possible materials for their applications. With this in place, devices can be designed that essentially range from sensors, displays, lasers, photonic circuits, and much more. Further knowledge of optical materials will, indeed, help make way for innovations in the field with countless options for practical and applied achievements.

4.1. Advanced materials for optical devices

The development of advanced materials has significantly contributed to the progress of optical devices. This section will delve into the diverse range of materials used in optical devices, such as semiconductors, dielectrics, metals, and nanomaterials. It will explore the unique optical properties of these materials, including their refractive index, transparency, and nonlinear behaviour. Discussions may include topics such as semiconductor quantum dots, perovskite materials, and 2D materials like graphene and transition metal dichalcogenides.[28] Furthermore, the section will highlight the importance of material engineering for achieving desired optical device functionalities, such as light emission, modulation, and sensing.

4.2. Metamaterials and plasmonics

One among the two most exciting research fields in optical materials is metamaterials/plasmonics. This section describes the concept of metamaterials, which are artificial materials with properties not found in nature. It will also consider their optical properties such as negative refraction, extraordinary transmission, and perfect absorption. Lens designs based on metamaterials, cloak devices, and super-resolution imaging will be among the topics discussed. Then we step into the world of plasmonics: it deals with the interaction of light with surface plasmons in metallic nanostructures.[29] The discussions will include plasmonic phenomena such as localized surface plasmon resonance and surface-enhanced Raman scattering, together with their applications in sensing, spectroscopy, and light manipulation. Figure 5 presents a visual summary of the fundamental principles and real-world applications of metamaterials and plasmonics two groundbreaking domains in modern optics and nanophotonics. (a) *Metamaterials*, (b) *Plasmonics*, (c) *Applications*. These innovations demonstrate how metamaterials and plasmonics are reshaping possibilities in optical device design and functionality.

4.3. Organic and hybrid materials in photonics

Organic and hybrid materials show immense versatility, making them useful in photonics as well. This section will describe the special features of organic materials, such as tunability, flexibility, and large nonlinear response. Topics to be discussed will include organic photovoltaics, organic light-emitting diodes (OLEDs), and organic lasers.[30,31] In addition, a special emphasis will be given to hybrid materials that carry combined properties from different classes of materials, such as organic-inorganic perovskites, quantum dots, and hybrid nanomaterials. It will discuss their optical properties, synthesis techniques, and applications in optoelectronic devices, solar cells, and light-emitting devices. Harnessing possibilities offered at the frontier of optical materials, this section shall discuss the very recent advances and emerging viewpoints of the field. The combination of advanced materials for optical device engineering with metamaterials, plasmonics, and organic/hybrid materials offers researchers new tools to push boundaries even further in enabling enhanced light-matter interactions and truly innovative photonic technologies. Table 2 lists the types of organic and hybrid materials used in photonics, giving some examples under each category. Due to their distinguished optical and electronic properties coupled with cheap and flexible device fabrications, organic and hybrid materials continue to attract attention in photonics. Organic semiconductors like polythiophenes, pentacene, P3HT, and PCDTBT have tenable energy gaps and high charge carrier mobilities, hence being applied in organic light-emitting diodes (OLEDs), organic solar cells, and organic field-effect transistors (OFETs). Organic dyes like rhodamine, coumarin, cyanine, and perylene show absorption and fluorescence properties, allowing their use in optoelectronic devices, sensors, and imaging. Organic polymers such as poly(p-phenylene vinylene) (PPV) and P3OT combine the traits of both organic and polymeric materials, thus offering good optical properties and processability. On the other hand, hybrid perovskite materials like CH3NH3PbI3, CsPbBr3, and CH3NH3PbCl3 have been considered prospective candidates for photovoltaic application owing to their intense light absorption and long carrier diffusion lengths. Organic-inorganic hybrid materials such as organometallic complexes and conjugated polymer blends are a synergistic convergence of organic and inorganic constituents. The materials display enhanced charge transport ability, improved stability, and tenable optoelectronic properties, so that they have become useful for several photonic applications like light-emitting devices and photodetectors. Examining various types of organic and hybrid materials in photonics would spill over the probability for designing and manufacturing advanced optoelectronic devices with better performance and functions. These materials provide versatility, tunability, and moreover, are compatible with flexible substrates for realizing novel photonics technologies for more applications, such as display, lighting, sensing, and harvesting.

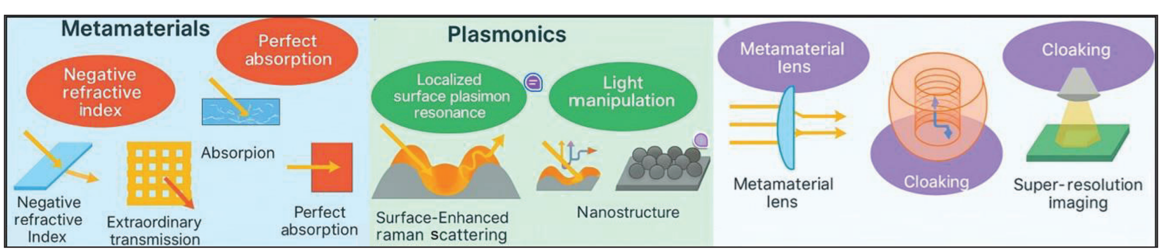

Figure 5: Fundamental concepts and applications of metamaterials and plasmonics.

Table 2: Types and examples of organic and hybrid materials in photonics.

Material type	Examples
Organic semiconductors	Polythiophenes, Pentacene, P_3HT, PCDTBT
Organic dyes	Rhodamine, Coumarin, Cyanine, Perylene
Organic polymers	Poly(p-phenylene vinylene) (PPV), P3OT
Hybrid perovskites	$CH_3NH_3PbI_3$, CsPbBr3, $CH_3NH_3PbCl_3$
Organic-inorganic hybrids	Organometallic Complexes, Conjugated Polymer Blend

5. PHOTONIC DEVICES TRANSFORMING INDUSTRIES

Photonic devices leverage the power of light to enable advanced sensing, imaging, energy conversion, communication, and medical applications. Photonic sensors are revolutionizing industries by providing highly sensitive and accurate measurements in areas such as temperature, pressure, and gas detection. These sensors find applications in automotive, aerospace, environmental monitoring, and industrial sectors, enabling improved process control, safety, and efficiency. Imaging devices, including CCD and CMOS image sensors, infrared cameras, and optical coherence tomography (OCT) systems, have transformed medical diagnostics, security systems, and quality control processes. These devices capture high-resolution images[32] and enable non-invasive and real-time imaging, enhancing our understanding of biological structures, identifying defects in manufacturing, and improving surveillance capabilities. Photovoltaics, represented by silicon solar cells, thin-film solar cells, and multi-junction solar cells, have revolutionized the renewable energy industry. These devices convert sunlight into electricity, providing clean and sustainable energy solutions. Photovoltaics have made significant advancements in efficiency and cost-effectiveness, driving the adoption of solar power as a viable energy source worldwide.

Optical communication systems have transformed the telecommunications industry, enabling high-speed data transmission over long distances. Fiber-optic communication systems, optical transceivers, and wavelength division multiplexing (WDM) technologies have dramatically increased data transmission capacity, leading to faster internet connections, improved network reliability, and seamless global communication. In the field of biophotonics, photonic devices are making a significant impact on medical diagnostics and treatments. Fluorescence microscopy allows for visualization of cellular and molecular processes, aiding in disease diagnosis and drug development. Laser-based medical treatments offer precise and minimally invasive procedures, while optical biosensors enable rapid and sensitive detection of biological analytes for healthcare diagnostics and environmental monitoring. These examples demonstrate the transformative power of photonic devices in various industries, enhancing efficiency, accuracy, and sustainability. Continued research and development in photonic technologies will lead to further advancements, unlocking new possibilities and applications in areas such as quantum photonics, integrated photonics, and advanced imaging systems. The integration of photonics with other emerging technologies will shape the future of industries, enabling smarter and more interconnected systems for the benefit of society.

5.1. Photonic sensors and imaging devices

The photonic sensors and imaging devices have transformed industries by offering high-precision measurements, imaging, and detection. This section will cover the recent advances in photonic sensors, which encompass optical fibre sensors, photonic integrated sensor arrays, and nanophotonic sensors.[33] The section will explore their applications in areas such as environmental monitoring, healthcare, industrial automation, and aerospace. In addition, the section will discuss imaging devices such as digital cameras, infrared cameras, and biomedical imaging systems, emphasizing their role in scientific research, medical diagnostics, and security applications. The emerging trends of hyperspectral imaging and wearable sensors will also be discussed concerning industrial and societal impacts. Figure 6 provides an organized overview of the ecosystem of photonic sensors and imaging technologies, connecting foundational components with their practical applications and future directions.

Under the broad umbrella of applications, the figure shows how photonic systems enable advancements in healthcare (e.g., patient monitoring), industrial automation (e.g., process control and safety diagnostics), environmental assessment, and aerospace (e.g., precision sensing in harsh conditions). Finally, on the far right, the diagram illustrates emerging trends:

- Hyperspectral imaging captures rich spectral data across numerous bands, useful in agriculture, defense, and environmental analysis.
- Wearable sensors represent the forefront of mobile diagnostics and personalized health monitoring, reflecting the intersection of photonics, data science, and biomedicine.

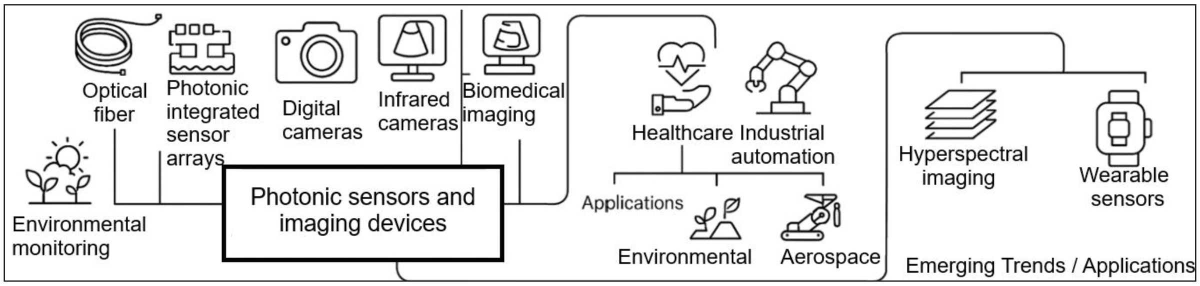

Figure 6: Technologies and applications of photonic sensors and imaging devices.

5.2. Photovoltaics and solar energy applications

Photonic equipment plays a pivotal role in the photovoltaic and solar energies, conditioning the developments of renewable energy generation.[34] This section shall consider photovoltaic devices including solar cells and solar panels, and their pathways of increasing efficiency, cost reduction, and new technologies-the likes of multi-junction solar cells, perovskite solar cells, and tandem solar cells. This shall also consider other solar applications apart from electricity, such as solar thermal, concentrated solar power, and solar fuels, where photonic materials and light management techniques along with device design improve solar energy conversion efficiency and scaling-up.[35] In the Solar Energy Technologies section, primary components of photovoltaic energy conversion systems, solar cells, and solar panels are highlighted. These are solar electric generation from sunlight and have been continuously developed in their efficiency, manufacturability, and material composition. The Efficiency Improvement section points out two main vectors of photovoltaic innovation: light management and cost lowering techniques. Light management covers anti-reflection coatings, photonic crystals, surface texturing, etc., which aim to maximize absorption and minimize reflection losses. On the other hand, cost-lowering methods now deal mostly with efficient use of materials, low-temperature processing, and simplification of module assembly. The Emerging Technologies section shows multi-junction solar cells, perovskite solar cells, and tandem architectures developed to outperform efficiency ceilings of conventional solar cells. Multi-junction cells are made by layering various materials to detect an extended solar spectrum band. Perovskites provide a low-cost, solution-processable alternative with tenable bandgaps, while tandem solar cells electrically combine two materials, like silicon and perovskite, exploiting their complementary absorption properties. The Solar Energy Applications branch takes a step outside solar electricity generation with a few systems in solar thermal, capturing sunlight as heat to be used for industrial and residential purposes; CSP (concentrated solar power), which focuses sunlight using mirrors or lenses into a receiver; and solar fuels, which store solar energy in chemical forms, such as H2 via photocatalysis. Photonic engineering helps each of these applications through light capture, thermal retention, or catalytic efficiency enhancement.

5.3. Optical communication systems and networks

The invention of optical communication systems and networks has drastically transformed the telecommunications industry, resulting in data being transmitted at high speed while remaining connected. This section will cover developments in optical communication technologies, namely optical fibres, wavelength division multiplexing, and optical switches.[36,37] Topics will include fibre-optic networks, optical amplifiers, and photonic integrated circuits for data transmission. It will further shed light on recent developments in free-space optics, visible light communication, and quantum communication networks. Photonic devices will be stressed while providing high data rates, low latency, and secure communication, thus giving birth to advances in telecommunication, internet connectivity, and data centers.[38]

5.4. Biophotonics and medical applications

Over the dawn of the 21st century, the field of biophotonics has blossomed into a multidisciplinary area combining photonics, biology, and medicine, essentially transforming diagnosis, imaging, and therapy in the health sciences. This section will dwell on some biomedical applications of photonics, such as optical imaging methods (fluorescence imaging, optical coherence tomography), biophotonic sensors, and photonic therapies (photodynamic therapy, laser surgery).[39] It will be focusing on how photonic devices lend their hand to medical diagnostics, drug discovery, bioimaging, and personalized medicine. The section may further entertain topics on new trends, including wearable photonics and point-of-care diagnostics, and assess how these might influence healthcare delivery.[40]

6. CONCLUSION

This review highlights the transformative potential of photonic devices across multiple industries. Advancements in quantum optics, integrated photonics, and novel optical materials are redefining communication, imaging, energy, and healthcare technologies. Photonic innovations such as high-speed data transmission, quantum cryptography, biosensing, and solar energy conversion are not only pushing technological boundaries but also enabling sustainable and efficient solutions. The integration of light-based technologies with emerging fields continues to open new avenues for research and real-world applications. Looking ahead, interdisciplinary collaboration and focused innovation will be vital to overcoming existing challenges and unlocking the full promise of photonics in shaping the future.

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Ethical approval: Institutional Review Board approval is not required.

Declaration of patient consent: Patient's consent not required as there are no patients in this study.

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Conflicts of interest: There are no conflicts of interest.

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