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Perspective Article

Photonics sensors: A perspective on current advancements, emerging challenges, and potential solutions (Invited)

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ABSTRACT

Photonic sensors play a vital role in the modern world, revolutionizing various industries with their efficiency and precision. These sensors utilize light particles (photons) to detect, measure, and analyze different parameters such as light intensity, wavelength, phase, and polarization. One of their key advantages lies in their ability to offer highly sensitive, fast, and accurate measurements across a wide range of applications. In healthcare, they are used in medical imaging technologies like optical coherence tomography for non-invasive diagnostics and imaging of tissues. Additionally, photonic sensors have transformed environmental monitoring, allowing real-time analysis of pollutants, gases, and other substances in air and water. Moreover, their application extends to defence and security, where they are utilized in surveillance, reconnaissance, and laser-based defence systems. In this concise paper, we aim to offer our insights into the latest advancements, emerging challenges, and potential solutions in the ongoing development of photonic sensors.

Introduction

Integrated photonics is a specialized field within optics and photonics that focuses on miniaturizing and combining optical components and systems onto a single chip or substrate [1]. This technological area involves manufacturing photonic devices like waveguides, modulators, detectors, and light sources utilizing materials such as silicon or III-V semiconductors [2]. Integrated photonics authorises the manipulation and management of light at micro- and nanoscales, resulting in compact and efficient photonic circuits applicable across various domains [3]. By integrating multiple optical functionalities onto a single chip, integrated photonics provides benefits like reduced size, weight, power consumption, and cost in contrast to traditional optical setups. This technology is pivotal in telecommunications, data communications, sensing, imaging, and quantum information processing, catalyzing advancements in high-speed data transmission, biomedical imaging, and next-generation computing architectures [4].

Photonic sensors and electronic sensors each offer distinct pros and cons, making them suitable for diverse applications based on specific requirements (see Table 1). Photonic sensors excel in certain areas due to their incomparable properties [5]. One major advantage of photonic sensors over electronic sensors is their resistance to electromagnetic interference (EMI). Since photonic sensors use light signals instead of electrical signals, they are less susceptible to interference from electromagnetic fields, making them ideal for applications in environments with high EMI, such as power plants or industrial settings [6]. Photonic sensors also offer higher sensitivity and accuracy for certain measurements, especially in applications necessitating precise detection of light intensity, wavelength, or refractive index changes. They can be more appropriate for long-distance sensing due to the low loss of light in optical fibers compared to electrical signals in wires. Nevertheless, photonic sensors can be more complex and expensive to manufacture and integrate compared to electronic sensors. They may also require specialized components and expertise for calibration and maintenance. Additionally, photonic sensors typically rely on light sources such as lasers, which can pose safety concerns and require vigilant handling. In contrast, electronic sensors are often simpler, more cost-effective, and easier to integrate into electronic circuits, making them more suitable for certain applications where cost, simplicity, and familiarity are key factors. Ultimately, the choice between photonic and electronic sensors depends on the specific sensing requirements, environmental conditions, and budget constraints of the intended application. In this concise paper, our objective is to delve into the present state of photonic sensors, highlighting the existing challenges and exploring potential solutions.

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Table 1
Differences between electronic sensors and photonic sensors.

Criteria	Electronic sensors	Photonic sensors
Nature of Sensing	Measure electrical properties (voltage, current)	Measure light or optical properties
Sensing Principle	Utilizes electrical signals or changes	Utilizes light signals or changes
Detection Range	Typically suited for small-scale measurements	Suited for large-scale measurements
Sensitivity	Can be highly sensitive	Can be extremely sensitive
Interference	Susceptible to EMI	Generally, less susceptible to EMI
Bandwidth	Limited by electrical characteristics	Can have broader bandwidth
Environmental Factors	Susceptible to noise, temperature, and EMI	Less affected by noise and EMI
Speed of Response	Fast response time	Very fast response time
Cost	Cost-effective for many applications	Can be higher cost depending on application
Energy Consumption	Moderate to high	Moderate
Applications	Various applications in electronics, automotive, biomedical	Fiber optics, telecommunications, environmental monitoring

The origins of photonic sensors trace back to the early 20th century amidst significant strides in optics and photonics. A pivotal moment emerged in the 1950s and 1960s with the development of fiber optics, a breakthrough enabling the transmission of light through slender glass fibers across extensive distances [7]. This advancement laid a solid foundation for leveraging light-based sensors in diverse applications. The first practical photonic sensors surfaced in the 1970s, coinciding with the invention of the optical fiber sensor by George Hockham and Charles Kao, a development that sparked a revolution in telecommunications and sensing technologies. Subsequent decades witnessed a rapid expansion in photonic sensor research propelled by innovations in laser technology, semiconductor materials, and signal processing methods [8]. Today, photonic sensors have integral roles across multiple industries, including telecommunications, biomedical diagnostics, environmental monitoring, and industrial automation, offering unmatched precision and sensitivity in measuring a broad spectrum of physical quantities.

Photonic sensors play a critical role in modern technology and industry due to their unique capabilities and advantages [5,9,10]. These sensors operate based on the interaction of light with materials under investigation, offering non-contact and remote sensing capabilities that are highly desirable in applications where traditional electrical sensors may be impractical or insufficient. Additionally, photonic sensors can be miniaturized and integrated into complex systems, enabling real-time monitoring and control in fields like healthcare, environmental monitoring, telecommunications, and manufacturing [11,12]. Their versatility and reliability make photonic sensors indispensable for advancing technology and addressing challenges across a wide range of industries.

Recent advancements in photonic sensor technology have ushered in a new era of precision and sensitivity, revolutionizing various fields from healthcare to environmental monitoring [13]. Innovations in sensor design have led to the development of highly compact and versatile devices capable of detecting a wide range of physical and chemical parameters with unprecedented accuracy. Fabrication techniques such as nanolithography and 3D printing have enabled the production of sensors with intricate structures at the nanoscale, enhancing their sensitivity and response times [14]. Materials research has played a crucial role in expanding the capabilities of photonic sensors, with the exploration of novel materials such as plasmonic nanoparticles and quantum dots, offering enhanced signal amplification and multiplexing capabilities [15]. Furthermore, integration methods have facilitated the seamless incorporation of photonic sensors into various platforms, including wearable devices and Internet of Things (IoT) systems, enabling real-time monitoring and data analytics [16]. These collective advancements promise to significantly impact industries ranging from biomedicine to telecommunications, paving the way for innovative solutions to complex challenges.

Several companies are actively involved in the manufacturing of photonic sensors. Companies such as Hamamatsu Photonics [17], Omron Corporation [18], and Luna Innovations [19] specialize in developing and producing photonic sensors for a wide array of applications. Hamamatsu Photonics, based in Japan, is a renowned manufacturer of photomultiplier tubes and photodiodes used in medical imaging, analytical instruments, and industrial automation. Omron Corporation, headquartered in Japan, focuses on producing fiber optic sensors and components that are integrated into automated machinery for precision detection and monitoring. Luna Innovations, based in the United States, specializes in fiber optic sensing technologies used in structural health monitoring, aerospace, and oil and gas industries. These companies are at the forefront of advancing photonic sensor technology, contributing to innovations that enhance the performance and reliability of modern sensing systems. While photonic sensors have experienced remarkable advancements, they still face several obstacles hindering their widespread adoption and effectiveness. Sensitivity limitations remain a critical challenge, particularly in detecting low-concentration analytes or weak signals, necessitating further improvements in signal amplification and noise reduction techniques [20]. Environmental robustness is another concern, as photonic sensors may be susceptible to fluctuations in temperature, humidity, and electromagnetic interference, compromising their reliability in harsh operating conditions [21]. Additionally, ensuring compatibility with current infrastructure presents a challenge, as photonic sensor technologies need to align with existing standards and protocols to facilitate seamless integration and interoperability. Addressing these obstacles requires interdisciplinary collaboration and continued research efforts to enhance the performance, reliability, and versatility of photonic sensors for diverse applications.

General categories of photonic sensors

The field of photonic sensors encompasses a diverse range of technologies, each classified into four general types based on their design, platform and applications as shown in Fig. 1. I) *Optical Fiber-Based Sensors*: These sensors utilize optical fibers as the core component for detecting changes in various parameters like temperature, pressure, or chemical composition [22,23]. The principle involves modulation of light signals propagating through the fiber, which can be altered by external influences, allowing for precise measurements; II) *Integrated Photonic Sensors*: This category involves sensors that integrate photonic components on a single chip. By leveraging advanced nanofabrication techniques, these sensors can achieve high sensitivity and compactness. Integrated photonic sensors are often used in applications requiring miniaturization and enhanced performance; III) *Wearable Sensors*: These are photonic sensors designed to be integrated into wearable devices, such as smart clothing or health monitoring gadgets. They empower non-intrusive monitoring of vital signs like heart rate, blood oxygen levels, or even environmental factors, offering continuous data collection for health and fitness applications; IV) *Metasurface (MS)-Based Sensors*: MSs are artificially engineered surfaces composed of subwavelength structures that can manipulate light in unique ways. MS-based sensors utilize these properties to detect and analyze light signals for applications ranging from imaging to spectroscopy, offering unprecedented control over light-matter interactions [24]. Each type of photonic sensor brings its advantages and applications to the table, contributing to the advancement of sensing technologies across various fields including healthcare, environmental monitoring, and industrial process control. The diversity within this field underscores the versatility and potential of photonic sensing in addressing complex

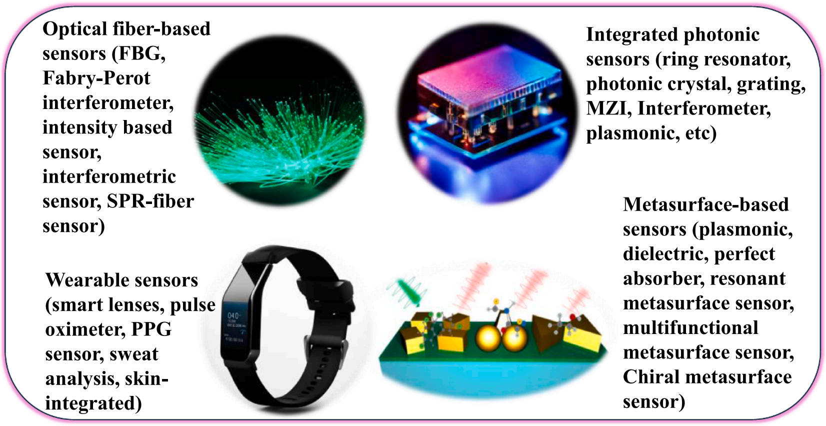

Fig. 1. Types of photonic sensors based on design, platform, and applications.

measurement challenges.

I) Optical fiber-based sensors are a sophisticated class of sensors that utilize the properties of light transmission through optical fibers to measure various physical, chemical, and biological parameters [16,25,26]. These sensors work on the principle of detecting changes in the intensity, phase, or polarization of light as it interacts with the surrounding environment or with specific analytes [27]. One common type of optical fiber sensor is the fiber Bragg grating (FBG), which consists of periodic variations in the refractive index along the core of the fiber. FBGs are extensively employed in strain and temperature sensing applications [28]. For instance, in structural health monitoring, FBG sensors can be embedded into buildings or bridges to monitor strain and temperature changes, providing critical data for maintenance and safety [29,30]. Another significant example is the use of optical fiber sensors in biomedical applications, such as glucose sensing for diabetes management. By coating the fiber with specific biochemical materials that react with glucose, changes in light transmission through the fiber can indicate glucose levels. This approach offers a minimally invasive and continuous monitoring solution. Recently, a novel all-fiber glucose sensor was introduced, utilizing a helical intermediate-period fiber grating (HIPFG) fabricated through a precise hydrogen/oxygen flame heating method [31]. The HIPFG, spanning 1.7 cm with a period of 35 μm, displays exceptional characteristics in its transmission spectrum, revealing four sets of double dips with minimal insertion losses and robust coupling strengths. Remarkably, the HIPFG showcases an average refractive index sensitivity of 213.6 nm/RIU within the refractive index range of 1.33–1.36, peaking at 472 nm/RIU at a refractive index of 1.395. Additionally, its low-temperature sensitivity of 3.67pm/ °C ensures reliable self-temperature compensation during glucose detection. In glucose-sensing trials, the HIPFG sensor demonstrated a high detection sensitivity of 0.026 nm/(mg/mL) alongside a commendable limit of detection (LOD) of 1 mg/mL. Notably, the sensor exhibits exceptional stability over 2 h, affirming its suitability for prolonged and precise glucose monitoring applications.

Optical fibers can also be employed in environmental sensing, like detecting pollutants in water or gases, based on changes in light properties caused by the presence of specific substances. Both photonic crystal (PC) fiber sensors [15] and D-shaped fiber sensors [32] demonstrate the innovative potential of optical fiber technology in advancing sensing capabilities across various fields including biomedical diagnostics, environmental monitoring, and industrial automation. An innovative design for a Rayleigh-based optical fiber sensor tailored for monitoring water levels and temperature within storage nuclear fuel pools was presented [33]. This sensor was engineered to withstand extreme conditions akin to those encountered during events like the Fukushima-Daiichi incident, with temperatures reaching up to 100 °C and radiation doses nearing ~20 kGy. Leveraging optical frequency domain reflectometry, the sensor utilized a radiation-resistant silica-based optical fiber as its sensing probe. Through rigorous testing in a dedicated simulation bench replicating both standard and emergency scenarios, the sensor's efficacy and durability in accurately measuring water levels, extrapolated from temperature profiles along the fiber's length was validated. The prototype offers seamless integration into existing nuclear facilities without invasive procedures. These findings mark a significant advancement, affirming the system's capability to address operational and emergency challenges, providing precise distributed profiles of water level (0–to–5 m) and temperature (20–to–100 °C) with exceptional resolution, surpassing 3 cm and ~0.5 °C, respectively. These innovative sensors stand poised to enhance safety measures in current and future nuclear power plants as critical safeguards.

II) Integrated photonic sensors epitomize a leading-edge technology that merges optics and microelectronics onto a unified chip platform. These sensors harness photonic integrated circuits (PICs) to amalgamate various optical components like waveguides, light sources, detectors, and modulators onto a compact chip-scale device. Through the miniaturization of optical elements and their integration with electronic circuitry, integrated photonic sensors offer notable benefits including compact size, low power consumption, and heightened sensitivity. They can be customized for specific applications such as biomedical diagnostics, environmental monitoring, and telecommunications. Integrated photonic sensors facilitate precise measurements of parameters such as temperature, pressure, refractive index, and chemical composition with enhanced accuracy and reliability. As the field of integrated photonics continues to progress, these sensors hold significant promise for transforming sensing technology by enabling cost-effective, scalable, and adaptable solutions across diverse applications.

Plasmonic sensors represent another category of integrated photonic sensors, offering substantial potential in sensing technology by their distinctive capacity to recognize and study molecular interactions on a remarkably minute scale [34,35]. These sensors utilize surface plasmon resonance (SPR) phenomena, where light interacts with free electrons at a metal-dielectric interface, leading to highly sensitive detection of changes in refractive index caused by target molecules [36,37,38,39,40].

The significance of plasmonic sensors lies in their capability to provide real-time, label-free detection of biomolecular interactions, making them invaluable in applications such as medical diagnostics, drug discovery, environmental monitoring, and food safety [41]. Plasmonic sensors offer advantages like ultra-high sensitivity, rapid response times, and the potential for miniaturization and integration into portable devices [42]. They contribute to advancing healthcare by enabling early disease detection and personalized medicine approaches. Additionally, plasmonic sensors are vital in improving the efficiency and accuracy of chemical and biological analyses, thus driving innovations in various industries and research fields [43]. Metal-insulator-metal (MIM) based plasmonic sensors have garnered significant attention within the research community, propelled by their extraordinary properties and versatile applications [35,44,45,46,47,48,49].

Integrated photonic sensors offer several advantages over traditional fiber-based sensors, making them a compelling choice for certain applications. One key advantage is their compactness and scalability. Integrated photonic sensors can incorporate multiple optical components onto a single chip, reducing overall size and complexity compared to systems using bulky optical fibers and discrete components. This miniaturization enables integration with other electronics on a chip, facilitating easier integration into complex systems and reducing the overall system footprint. Additionally, integrated photonic sensors typically exhibit lower power consumption and higher sensitivity due to optimized light-matter interactions within the chip-scale device. They are also more robust against environmental factors like temperature variations and mechanical stress, as the optical components are tightly integrated and protected within the chip structure. Furthermore, integrated photonic sensors offer improved manufacturability and potential for mass production using standard semiconductor fabrication processes, which can lead to lower costs and enhanced reliability. Overall, the compactness, scalability, sensitivity, and integration capabilities of integrated photonic sensors make them a preferred choice for next-generation sensing applications over traditional fiber-based sensors in certain scenarios.

III) Wearable sensors are compact, portable devices integrated into clothing or accessories that can monitor various physiological and environmental parameters. These sensors are designed to seamlessly collect data about an individual's health and activity in real-time. Common types of wearable sensors include heart rate monitors, accelerometers for tracking movement and activity levels, temperature sensors, and sweat sensors that can analyze biomarkers [50,51]. A novel soft wearable system characterized by its innovative design was proposed, which incorporates a soft polymer matrix embedding an array of FBGs [52]. The design facilitates excellent adhesion to the body, ensuring comfort for the wearer, while simultaneously enabling the simultaneous recording of seismocardiogram (SCG) signals from multiple measuring sites. Through a feasibility assessment conducted on healthy volunteers, it was demonstrated that the soft wearable system serves as a suitable wearable solution for heart rate monitoring. The accuracy of heart rate estimation was significantly influenced by sensor positioning and is notably enhanced by employing a multi-sensor configuration. Wearable sensors also have applications in fitness tracking, healthcare monitoring, and sports performance analysis. They provide valuable insights into an individual's health and wellness, enabling personalized and preventive healthcare interventions. The continuous advancements in materials, electronics, and data analytics are driving the development of increasingly sophisticated and user-friendly wearable sensor technologies [53].

One prominent example is wearable pulse oximeters, which use photonic sensors to measure oxygen saturation levels in the blood. It became a crucial tool during the COVID-19 pandemic due to its ability to monitor blood oxygen levels non-invasively. These compact devices typically incorporate light-emitting diodes (LEDs) and photodetectors to analyze how light is absorbed by blood vessels, providing real-time feedback on oxygen levels. Another example is wearable glucose monitors that employ optical sensors to continuously measure glucose levels in interstitial fluid, offering a less invasive alternative to traditional finger-prick methods for individuals with diabetes. Additionally, wearable sensors based on photonic principles are being developed for monitoring heart rate, hydration levels, and even detecting UV exposure for skin health. These wearable photonic sensors represent a noteworthy advancement towards personalized and continuous (24/7) health monitoring, enabling wearers to make informed decisions about their well-being in real time [54].

IV) MS-based photonic sensors represent a cutting-edge paradigm in sensing technology, leveraging the unique properties of MSs to enable highly sensitive and versatile detection capabilities across various domains [55]. MSs are two-dimensional arrays of subwavelength structures, engineered to manipulate light at the nanoscale, offering unprecedented control over the amplitude, phase, and polarization of light waves. By carefully designing the geometry, size, and arrangement of these nanostructures, metasurfaces can tailor optical properties with exquisite precision, enabling a myriad of functionalities in sensing applications. One of the remarkable aspects of MS-based photonic sensors is their ability to achieve enhanced light-matter interactions, leading to extraordinary sensitivity and selectivity. By exploiting localized surface plasmon resonances (LSPRs) or other resonant phenomena, MSs can concentrate electromagnetic fields into subwavelength volumes, enabling the detection of minute changes in the surrounding environment [56]. This sensitivity is particularly advantageous for detecting biomolecules, gases, chemicals, and other analytes at ultra-low concentrations, making MS sensors promising candidates for medical diagnostics, environmental monitoring, and industrial process control [57].

Moreover, MS-based photonic sensors offer unparalleled versatility and tunability, allowing for dynamic adjustment of sensing parameters to suit specific requirements. The optical properties of MSs can be tailored by changing the material composition, geometry, or illumination conditions, enabling real-time optimization of sensor performance. Additionally, MS sensors can be integrated with other photonic components, such as waveguides, resonators, and light sources, to create compact, multifunctional sensor platforms with enhanced functionality and miniaturization. In recent years, significant progress has been made in the development of MS-based photonic sensors across a wide range of spectral regions, including the visible, near-infrared, and terahertz regimes [58]. Researchers have demonstrated MS sensors for applications such as label-free biosensing, gas detection, strain sensing, and optical imaging, showcasing their potential to address diverse sensing challenges [59]. Furthermore, advancements in fabrication techniques, such as nanoimprint lithography (NIL), electron beam lithography (EBL), and self-assembly methods, have enabled the mass production of MS devices with high reproducibility and scalability, paving the way for commercialization and widespread adoption [60].

Integrated photonic sensors offer high sensitivity and precision within a compact form factor, ideal for biomedical diagnostics and environmental monitoring, although they come with high development costs and design complexity [61,62]. Optical fiber-based sensors are robust and flexible, excelling in long-distance sensing in harsh environments, which is valuable for structural health monitoring and industrial applications, despite challenges in installation and signal attenuation [12,34,63]. MS-based sensors provide exceptional spatial resolution and sensitivity to specific molecular signatures, making them suitable for advanced imaging and biochemical sensing, but their complex fabrication and limited scalability can be drawbacks [55,64]. Wearable sensors are designed for continuous, real-time health and fitness monitoring, offering user-friendly, non-invasive solutions, although they face limitations in battery life, accuracy due to movement artifacts, and data privacy concerns [65,66]. Ultimately, the best sensing configuration depends on the specific application requirements, including sensitivity, spatial resolution, environmental conditions, and practical considerations like cost and ease of use.

Fabrication methods

Fabrication methods for photonic sensors involve intricate processes aimed at creating precise optical components and structures on various substrates [2]. The types and details of such methods are displayed in Fig. 2. One common technique is photolithography, where a photoresist layer is patterned using light (UV or DUV) exposure through a mask, followed by etching to transfer the pattern onto the substrate. This method is used to fabricate waveguides, grating structures, and other optical modules with high resolution and accuracy. Another approach is EBL, which offers even finer feature resolution (sub-10 nm) by using a focused electron beam to directly write patterns on the substrate. NIL is a versatile nanofabrication technique used for creating patterns and structures at the nanoscale level. In NIL, a template with the desired pattern is pressed into a polymer film, transferring the pattern onto the substrate. This process enables the fabrication of high-resolution features with potential applications in photonic devices such as waveguides, photonic crystals, and optical gratings [67]. However, one of the limitations of NIL in manufacturing photonic devices is the challenge of achieving precise alignment and registration of multiple layers with nanoscale features. Additionally, the choice of suitable imprint materials and the risk of defects during the imprinting process can affect the quality and reliability of photonic components produced by NIL [68].

Thin film deposition methods like sputtering and chemical vapor deposition (CVD), physical vapor deposition (PVD), atomic layer deposition (ALD) and molecular beam epitaxy (MBE) are employed to deposit materials for creating optical coatings, metal layers for plasmonic sensors, and semiconductor layers for integrated photonic devices. The sol-gel and dip-coating method is a low-cost alternative to creating thin films of high quality for various applications. This technique involves repeatedly dipping a substrate into a sol solution and then withdrawing it, resulting in a uniform thin film upon drying and subsequent heat treatment. One advantage is its simplicity and precise thickness control over large areas, allowing for complex compositions and tailored optical properties with dopants [69]. However, challenges include potential film cracking during drying, difficulty achieving uniformity on non-planar substrates, and limited scalability for mass production. Controlling film porosity and refractive index is crucial for optimizing optical performance. Despite these limitations, the sol-gel method and dip-coating technique remain valuable for producing functional thin films in photonic devices, with ongoing efforts to improve performance and versatility through process optimization and material design [70]. Continued advancements in fabrication methods will further drive innovation and enable the development of more sophisticated and efficient photonic sensor devices.

Etching techniques are vital for creating precise patterns and structures on photonic device substrates. Reactive ion etching (RIE), a form of dry etching utilizing plasma, is widely used due to its high etch rate and ability to create deep and well-defined features in materials like silicon, III-V semiconductors, and dielectrics [2]. Wet chemical etching offers another method, selectively dissolving materials with chemical

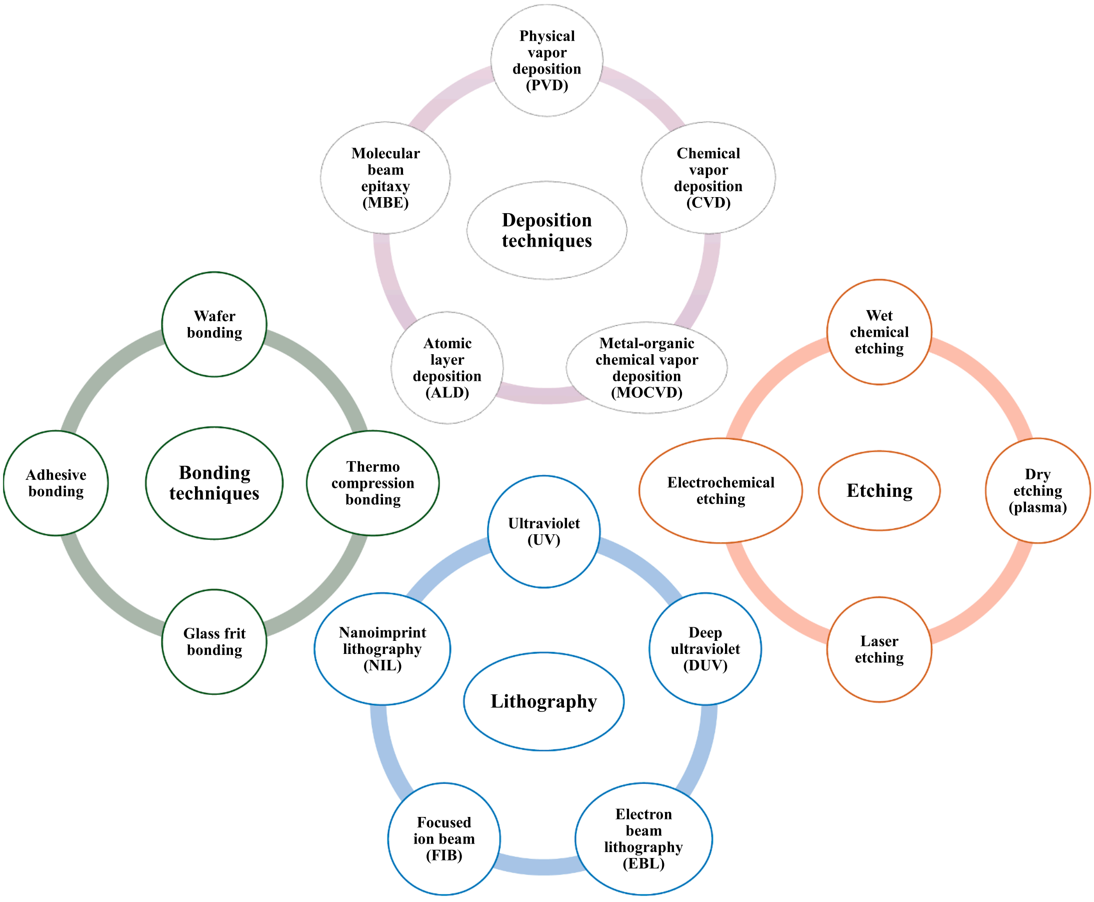

Fig. 2. Types of standard and advanced fabrication methods employed in the development of photonic devices.

solutions to achieve versatile patterning on different substrates. When combined with photolithography, etching allows for the precise definition of intricate patterns crucial for waveguides, μ-resonators, and gratings in photonic devices used across telecommunications, sensing, and biomedical fields. Laser machining and direct writing techniques enable precise structuring and modification of optical materials. 3D printing technologies are also emerging for rapid prototyping and fabrication of complex photonic sensor designs. These fabrication methods are critical for achieving the desired optical properties and functionalities essential for photonic sensors used in a diverse range of applications. Ongoing research emphasises enhancing etching technologies to achieve even higher resolution, uniformity, and precision in future photonic device fabrication.

Bonding techniques play a decisive role in the manufacture of photonic devices, enabling the integration of different components to produce complex optical systems. One commonly used bonding method is adhesive bonding, where optical components are joined using transparent adhesives that minimize light scattering and maintain optical quality [71]. Another technique is direct bonding, which involves bringing two substrates into close contact under controlled conditions such as temperature and pressure to facilitate bonding at the atomic or molecular level. Anodic bonding is another method used for bonding glass and silicon substrates, relying on the application of an electric field to create a strong bond at the interface. Wafer bonding, particularly fusion bonding, is utilized for integrating different material layers into photonic structures, offering precise alignment and high bonding strength [72]. These bonding techniques are essential for constructing photonic devices with intricate designs and functionalities, enabling advancements in optical communication, sensing, and imaging technologies. Ongoing research focuses on refining bonding processes to enhance device performance, reliability, and scalability for diverse photonic applications.

Navigating contemporary challenges: solutions and future outlook

Developing photonic sensors encounters numerous hurdles that demand cutting-edge solutions to elevate their capabilities. A primary obstacle involves enhancing sensitivity and reliability while reducing device size and cost. Photonic sensors often necessitate intricate configurations and precise alignment of components, which can incur high expenses and susceptibility to environmental disturbances. To tackle this, researchers are delving into integrated photonics, where various sensor elements are downscaled and consolidated onto a single chip, thereby bolstering reliability and curtailing manufacturing expenses. Another challenge lies in amplifying the detection threshold and specificity of photonic sensors, particularly for environmental monitoring and medical diagnostics. Researchers are exploring novel materials and nanostructures to enhance sensor efficacy, alongside utilizing sophisticated signal processing techniques to extract meaningful data from noisy signals. Furthermore, ensuring compatibility with existing infrastructure and adhering to standardization remains pivotal for the widespread adoption of photonic sensors across industries. Collaborative efforts involving researchers, industry collaborators, and policymakers are imperative to surmounting these challenges and unlocking the complete potential of photonic sensors to transform sensing technologies.

The readout unit of a photonic sensor chip presents several challenges that must be carefully managed to achieve optimal performance. One significant hurdle is attaining a high signal-to-noise ratio (SNR) during the detection process. Photonic sensors produce minute optical signals that are vulnerable to noise from sources like thermal fluctuations and environmental interference. Therefore, it is crucial to design a readout unit capable of accurately detecting and amplifying these weak signals while minimizing noise. Another complication arises from the necessity for precise calibration and stabilization of the readout electronics to ensure consistent and reliable sensor measurements under varying operating conditions. Additionally, integrating complex signal processing algorithms within the readout unit poses another challenge, demanding careful consideration of computational resources, power consumption, and real-time processing capabilities. Overcoming these challenges through innovative design strategies and advanced technologies is vital for enhancing the performance and reliability of photonic sensor readout units in practical applications.

We believe that the integration of sensors into existing systems presents both challenges and opportunities that warrant deeper exploration. At the forefront of these considerations are issues surrounding integration, scalability, and compatibility with existing systems, each of which carries its own set of complexities and implications. Sensor integration poses a significant challenge, particularly when incorporating diverse sensor types into a unified system. Integrating sensors from different manufacturers or with varying specifications can result in compatibility issues, leading to reduced system performance or functionality. Moreover, ensuring seamless communication and interoperability between sensors and the host system is paramount for achieving optimal performance and reliability. Incompatibilities in data formats, communication protocols, or power requirements can hinder integration efforts, necessitating careful planning and coordination throughout the integration process.

However, sensor integration also presents opportunities for innovation and optimization. By consolidating multiple sensors into a single platform, synergies can be leveraged to enhance system capabilities and performance. Integrated sensor systems can offer improved accuracy, sensitivity, and reliability compared to standalone sensors, making them well-suited for applications requiring complex sensing tasks or multi-parameter measurements. Furthermore, integrated sensor systems can streamline installation, maintenance, and operation, leading to cost savings and operational efficiencies over the long term.

Scalability is another critical consideration when it comes to sensor integration, especially in applications where the sensor network needs to accommodate varying scales of deployment or evolving requirements over time. Designing scalable sensor systems entails addressing challenges such as sensor density, network architecture, and data management to ensure seamless expansion or contraction of the sensor network as needed. Scalable sensor systems should be capable of accommodating additional sensors without necessitating significant modifications to the existing infrastructure, thereby facilitating flexibility and adaptability in response to changing needs or operational demands. However, achieving scalability in sensor integration also involves overcoming technical and logistical hurdles. For instance, scaling up sensor networks may introduce challenges related to power consumption, data bandwidth, and network congestion, necessitating careful resource allocation and optimization strategies. Moreover, maintaining consistency and coherence across the sensor network becomes increasingly challenging as the scale of deployment grows, requiring robust management and coordination mechanisms to ensure smooth operation and data integrity.

Compatibility with existing systems represents yet another facet of the sensor integration landscape, encompassing considerations such as hardware interfaces, software interoperability, and legacy system integration. Integrating new sensors into legacy systems or infrastructure can be fraught with compatibility issues, particularly when dealing with disparate technologies, protocols, or standards. Retrofitting existing systems to accommodate new sensors may require extensive modifications or upgrades, potentially introducing additional costs, complexity, and downtime. Nonetheless, compatibility with existing systems also presents opportunities for innovation and value creation. By leveraging standardized interfaces, open-source protocols, or modular architectures, sensor integration efforts can be streamlined, reducing compatibility barriers and accelerating deployment. Moreover, integrating new sensors with legacy systems can unlock new functionalities, enhance system performance, and extend the lifespan of existing infrastructure, thereby maximizing the return on investment and enabling seamless transition to advanced sensing technologies.

The future perspectives of photonic sensors hold tremendous promise for transforming several industries and applications. As technology progresses, photonic sensors are expected to become more compact, efficient, and versatile. Integration of photonics with emerging fields such as nanotechnology and artificial intelligence (AI) will enable the development of highly sensitive and intelligent sensors capable of detecting slight variations in physical, chemical, and biological parameters [73]. Photonic sensors will help enabling real-time, remote, and non-invasive monitoring in healthcare, environmental monitoring, industrial process control, and security applications. Moreover, the scalability of photonic sensor technologies will facilitate their deployment in large-scale sensor networks for smart cities and Internet of Things (IoT) applications. Future developments may also incorporate the use of advanced materials, for instance, two-dimensional materials and metamaterials, to achieve extraordinary sensor performance [74]. Quantum dots, with their size-dependent optical properties and easy integration into sensor platforms, offer remarkable opportunities for multiplexed sensing and single-molecule detection [75]. These materials, with their unique characteristics, pave the way for the development of highly efficient and versatile photonic sensor platforms with applications ranging from biomedical diagnostics to environmental monitoring and beyond. Overall, the future of photonic sensors is poised to revolutionize sensing capabilities, paving the way for safer, healthier, and more efficient societies.

As we have mentioned earlier, AI plays a crucial role in advancing photonic sensors and transforming their capabilities and applications. Photonic sensors, which rely on light to detect and measure various parameters, benefit immensely from AI-driven techniques like deep learning (DL). AI enables photonic sensors to handle complex data analysis and interpretation, improving their accuracy, sensitivity, and response time. DL models, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), can process large volumes of sensor data to identify patterns and anomalies that might be imperceptible to traditional methods. This capability enhances the reliability and robustness of photonic sensors across diverse fields including environmental monitoring, healthcare diagnostics, and industrial quality control. Furthermore, AI facilitates adaptive and self-learning photonic sensor systems, optimizing their performance in real-time based on evolving conditions. This synergy between DL and photonic sensors holds promise for future innovations in precision measurement and intelligent data-driven decision-making.

Concluding remarks

In recent years, photonic sensors have captured significant attention for their adaptability, precision, and potential to cater to a broad spectrum of sensing needs across various industries. Looking forward, a multitude of disruptive technologies, emerging applications, and evolving market dynamics stand poised to reshape the future landscape of photonic sensors. Integrated photonics represents a prominent disruptive force on the horizon. This technology involves consolidating photonic components onto a single chip, facilitating sensor miniaturization while concurrently enhancing performance, reliability, and cost-efficiency. Integrated photonics facilitates the creation of compact, portable photonic sensor devices well-suited for applications like point-of-care diagnostics, environmental monitoring, and industrial process control. As this technology matures, it is anticipated to drive the proliferation of photonic sensors across diverse sectors, supplanting conventional bulky sensor systems with solutions that are more streamlined, efficient, and scalable.

Another transformative trend influencing the trajectory of photonic sensors is the advancement of metamaterials and plasmonics. These specially engineered materials possess the ability to manipulate light at the nanoscale, conferring unprecedented control over light-matter interactions. Leveraging metamaterials, sensors can achieve heightened sensitivity, resolution, and selectivity, making them invaluable for tasks such as chemical sensing, bioimaging, and optical communications. By harnessing the distinct characteristics of metamaterials, researchers are pushing the boundaries of photonic sensor capabilities, thereby uncovering novel avenues for detecting and analyzing intricate phenomena with unparalleled precision.

Beyond technological innovations, emerging applications are driving demand for photonic sensors across a myriad of sectors including autonomous vehicles, augmented reality, and smart infrastructure. For instance, LiDAR sensors, grounded in photonic principles, are indispensable components for autonomous driving systems and robotics, facilitating distance measurement and high-resolution 3D mapping. With the automotive industry gravitating towards electrification and automation, the demand for LiDAR-based photonic sensors is poised for exponential growth, ushering in novel prospects for innovation and market expansion.

Furthermore, evolving market trends, such as an escalating emphasis on sustainability, safety, and connectivity, are reshaping the demand for photonic sensors in realms such as environmental monitoring, healthcare, and telecommunications. Photonic sensors are pivotal in detecting pollutants, monitoring emissions, and ensuring compliance with environmental standards amidst mounting concerns regarding air and water quality. Similarly, in healthcare, wearable photonic sensors are empowering continuous monitoring of vital signs, early disease detection, and personalized medical interventions, thereby bolstering patient outcomes and curbing healthcare expenditure. In summation, the future of photonic sensors is luminous, propelled by disruptive technologies, burgeoning applications, and dynamic market shifts. As advancements in integrated photonics, metamaterials, optical fiber and wearables gain momentum, photonic sensors will assume an increasingly pivotal role in reshaping our perception, interaction, and comprehension of the world. By harnessing the power of light, these sensors are poised to catalyze transformative innovations across diverse industries, charting a course towards a more interconnected, efficient, and sustainable future.

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CRediT authorship contribution statement

Muhammad Ali Butt: Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xavier Mateos:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Ryszard Piramidowicz:** Supervision, Resources, Project administration, Methodology.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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References

[1] L. Thylén, L. Wosinski, Integrated photonics in the 21st century, Photonics. Res. 2 (2) (2014) 75–81, https://doi.org/10.1364/PRJ.2.000075.

[2] M.A. Butt, Integrated optics: platforms and fabrication methods, Encyclopedia (Basel,. 2021) 3 (3) (2023), https://doi.org/10.3390/encyclopedia3030059.

[3] D. Dai, D. Liang, L. Liu, Introduction for the Integrated Photonics: challenges and Perspectives feature, Photonics. Res. 3 (5) (2015) IP1–IP2, https://doi.org/10.1364/PRJ.3.000IP1.

[4] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, Advancement in silicon integrated photonics technologies for sensing applications in near-infrared and mid-infrared region: a review, Photonics. 9 (5) (2022), https://doi.org/10.3390/photonics9050331.

[5] M.A. Butt, N.L. Kazanskiy, S.N. Khonina, G.S. Voronkov, E.P. Grakhova, R. V. Kutluyarov, A review on photonic sensing technologies: status and outlook, Biosensors 13 (5) (2023), https://doi.org/10.3390/bios13050568.

[6] M. Shahbaz, M.A. Butt, R. Piramidowicz, A concise review of the progress in photonic sensing devices, Photonics. 10 (6) (2023), https://doi.org/10.3390/photonics10060698.

[7] R. Tricker, 1 - The history of fiber optics, in: R. Tricker (Ed.), Optoelectronics and Fiber Optic Technology, Newnes, Oxford, 2002, pp. 1–35, https://doi.org/10.1016/B978-075065370-1/50003-9.

[8] B. Culshaw, A. Kersey, Fiber-Optic Sensing: a Historical Perspective, J. Light. Technol. 26 (9) (2008) 1064–1078, https://doi.org/10.1109/JLT.0082.921915.

[9] L. Hajshahvaladi, H. Kaatuzian, M. Danaie, A very high-resolution refractive index sensor based on hybrid topology of photonic crystal cavity and plasmonic nested split-ring resonator, Photonics Nanostructures - Fundam. Appl. 51 (2022) 101042, https://doi.org/10.1016/j.photonics.2022.101042.

[10] D. Gowdhami, V.R. Balaji, M. Murugan, S. Robinson, G. Hegde, Photonic crystal based biosensors: an overview, ISSS J. Micro Smart Syst. 11 (1) (2022) 147–167, https://doi.org/10.1007/s41683-022-00092-x.

[11] M.A. Butt, Numerical assessment of a metal-insulator-metal waveguide-based plasmonic sensor system for the recognition of tuberculosis in blood Plasma, Micromachines. (Basel) 14 (4) (2023), https://doi.org/10.3390/mi14040729.

[12] M.A. Butt, G.S. Voronkov, E.P. Grakhova, R.V. Kutluyarov, N.L. Kazanskiy, S. N. Khonina, Environmental monitoring: a comprehensive review on optical waveguide and fiber-based sensors, Biosensors 12 (11) (2022), https://doi.org/10.3390/bios12111038.

[13] A. Aksnes, Photonic Sensors for Health and Environmental Monitoring, in: M.-I. Baraton (Ed.), Sensors for Environment, Health and Security, Springer Netherlands, Dordrecht, 2009, pp. 191–203, https://doi.org/10.1007/978-1-4020-9009-7_12. Ed.

[14] H. Gao, J. An, C.K. Chua, D. Bourell, C-N. Kuo, D.T.H. Tan, 3D printed optics and photonics: processes, materials and applications, Materialstoday 69 (2023) 107–132.

[15] M. Rachana, I. Charles, S. Swarnakar, S.V. Krishna, S. Kumar, Recent advances in photonic crystal fiber-based sensors for biomedical applications, Opt. Fiber Technol. 74 (2022) 103085, https://doi.org/10.1016/j.yofte.2022.103085.

[16] R. Jha, P. Mishra, S. Kumar, Advancements in optical fiber-based wearable sensors for smart health monitoring, Biosens. Bioelectron. 254 (2024) 116232, https://doi.org/10.1016/j.bios.2024.116232.

[17] 'Optical components | hamamatsu photonics'. Accessed: Apr. 19, 2024. [Online]. Available: https://www.hamamatsu.com/jp/en/product/optical-components.html?nfxsid=CjwKCAjwrIixBhBbEiwACEqDJa9nE_Jwcz07rG7N4gnAX-h0mWuvtUCj7COPkRBijpBR8WvEd7Fp-BoC4zQQAvD_BwE&gad_source=1&nfxsid=6622ac38077981713548344&nfxcgnid=1&gclid=CjwKCAjwrIixBhBbEiwACEqDJa9nE_Jwcz07rG7N4gnAX-h0mWuvtUCj7COPkRBijpBR8WvEd7Fp-BoC4zQQAvD_BwE.

[18] 'OMRON Global'. Accessed: Apr. 19, 2024. [Online]. Available: https://www.omron.com/global/en/.

[19] 'Luna Innovations | fiber optic sensing and measurement systems'. Accessed: Aug. 09, 2023. [Online]. Available: https://lunainc.com/.

[20] M. El Beheiry, V. Liu, S. Fan, O. Levi, Sensitivity enhancement in photonic crystal slab biosensors, Opt. Express 18 (22) (2010) 22702–22714. https://opg.optica.org/oe/fulltext.cfm?uri=oe-18-22-22702&id=206381.

[21] Z. Li, Biotoxoid photonic sensors with temperature insensitivity using a cascade of ring resonator and mach–zehnder interferometer, ACS. Sens. 5 (8) (2020) 2448–2456, https://doi.org/10.1021/acssensors.0c00622.

[22] Y. Wang, Biocompatible and biodegradable polymer optical fiber for biomedical application: a review, Biosensors 11 (12) (2021), https://doi.org/10.3390/bios11120472.

[23] M. Li, R. Singh, Y. Wang, C. Marques, B. Zhang, S. Kumar, Advances in novel nanomaterial-based optical fiber biosensors—a review, Biosensors 12 (10) (2022), https://doi.org/10.3390/bios12100843.

[24] J. Qin, S. Jiang, Z. Wang, X. Cheng, B. Li, Y. Shi, D.P. Tsai, A.Q. Liu, W. Huang, W. Zhu, Metasurface Micro/nano-optical sensors: principles and applications, ACS Nano 16 (8) (2022) 11598–11618, https://doi.org/10.1021/acsnano2c03310.

[25] R. Singh, W. Zhang, X. Liu, B. Zhang, S. Kumar, WaveFlex Biosensor: mXene-Immobilized W-shaped Fiber-Based LSPR sensor for highly selective tyramine detection, Opt. Laser Technol. 171 (2024) 110357, https://doi.org/10.1016/j.optlastec.2023.110357.

[26] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, Advancing frontiers: semiconductor fibers in modern technology, Opt. Commun. 560 (130495) (2024). https://www.sciencedirect.com/science/article/abs/pii/S0030401824002323?via%3Dihub.

[27] M. Elsherif, Optical fiber sensors: working principle, applications, and limitations, Adv. Photonics Res. 3 (11) (2022) 2100371, https://doi.org/10.1002/adpr.202100371.

[28] J.K. Sahota, N. Gupta, D. Dhawan, Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review, Opt. Eng. 59 (6) (2020) 060901, https://doi.org/10.1117/1.OE.59.6.060901.

[29] S. Xu, X. Li, T. Wang, X. Wang, H. Liu, Fiber bragg grating pressure sensors: a review, Opt. Eng. 62 (1) (2023) 010902, https://doi.org/10.1117/1.OE.62.1.010902.

[30] M. Chen, T. He, Y. Zhao, G. Yang, Ultra-short phase-shifted fiber bragg grating in a microprobe for refractive index sensor with temperature compensation, Opt. Laser Technol. 157 (2023) 108672, https://doi.org/10.1016/j.optlastec.2022.108672.

[31] J. Zhong, High-sensitivity optical fiber-based glucose sensor using helical intermediate-period fiber grating, Sensors 22 (18) (2022), https://doi.org/10.3390/s22186824.

[32] A.A. Melo, M.F.S. Santiago, T.B. Silva, C.S. Moreira, R.M.S. Cruz, Investigation of a D-shaped optical fiber sensor with graphene overlay, IFAC-PapersOnLine 51 (27) (2018) 309–314. https://www.sciencedirect.com/science/article/pii/S2405896318333329.

[33] S. Rizzolo, Real time monitoring of water level and temperature in storage fuel pools through optical fibre sensors, Sci. Rep. 7 (1) (2017) 8766, https://doi.org/10.1038/s41598-017-08853-7.

[34] W. Zhang, Humanoid shaped optical fiber plasmon biosensor functionalized with graphene oxide/multi-walled carbon nanotubes for histamine detection, Opt. Express 31 (7) (2023) 11788–11803, https://doi.org/10.1364/OE.486844.

[35] M.A. Butt, R. Piramidowicz, Orthogonal mode couplers for plasmonic chip based on metal–insulator–metal waveguide for temperature sensing application, Sci. Rep. 14 (1) (2024) 3474, https://doi.org/10.1038/s41598-024-54244-0.

[36] V. Brahmkhatri, P. Pandit, P. Rananaware, A. D'Souza, M.D. Kurkuri, Recent progress in detection of chemical and biological toxins in water using plasmonic nanosensors, Trends Environ. Anal. Chem. 30 (2021) e00117, https://doi.org/10.1016/j.teac.2021.e00117.

[37] Q. Duan, Y. Liu, S. Chang, H. Chen, J. Chen, Surface Plasmonic sensors: sensing mechanism and recent applications, Sensors 21 (16) (2021), https://doi.org/10.3390/s21165262.

[38] F. Haider, R.A. Aoni, R. Ahmed, G.A. Mahdiraji, M.F. Azman, F.R.M. Adikan, Mode-multiplex plasmonic sensor for multi-analyte detection, Opt. Lett. 45 (14) (2020) 3945–3948, https://doi.org/10.1364/OL.396340.

[39] Z. Wang, Novel optical fiber-based structures for plasmonics sensors, Biosensors 12 (11) (2022), https://doi.org/10.3390/bios12111016.

[40] M.R. Rakhshani, Narrowband plasmonic absorber using gold nanoparticle arrays for refractive index sensing, IEEE Sens. J. 22 (5) (2022) 4043–4050, https://doi.org/10.1109/JSEN.2022.3142655.

[41] Butt, M.A., 'Insight into plasmonics: resurrection of modern-day science (invited)', *Comput. Opt.*, 48, 1, 5–17.

[42] M.A. Butt, Racetrack ring resonator-based on hybrid plasmonic waveguide for refractive index sensing, Micromachines 15 (5) (2024) 610. https://www.mdpi.com/2072-666X/15/5/610.

[43] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, Plasmonic sensors based on metal-insulator-metal waveguides for refractive index sensing applications: a brief review, Phys. E Low-Dimens. Syst. Nanostructures 117 (2020) 113798, https://doi.org/10.1016/j.physe.2019.113798.

[44] Kazanskiy, N.L., Khonina, S.N., Butt, M.A., Kazmierczak, A., Piramidowicz, R., 'A numerical investigation of a plasmonic sensor based on a metal-insulator-metal waveguide for simultaneous detection of biological analytes and ambient temperature', 11, 10, 2551, 2021.

[45] M.R. Rakhshani, M.A. Mansouri-Birjandi, A high-sensitivity sensor based on three-dimensional metal–insulator–metal racetrack resonator and application for hemoglobin detection, Photonics Nanostruct. - Fundam. Appl. 32 (2018) 28–34, https://doi.org/10.1016/j.photonics.2018.08.002.

[46] M.R. Rakhshani, M.A. Mansouri-Birjandi, High-sensitivity plasmonic sensor based on metal–insulator–metal waveguide and hexagonal-ring cavity, IEEE Sens. J. 16 (9) (2016) 3041–3046, https://doi.org/10.1109/JSEN.2016.2522560.

[47] M.R. Rakhshani, M.A. Mansouri-Birjandi, High sensitivity plasmonic refractive index sensing and its application for human blood group identification, Sens. Actuators B Chem. 249 (2017) 168–176, https://doi.org/10.1016/j.snb.2017.04.064.

[48] M.R. Rakhshani, M.A. Mansouri-Birjandi, Utilizing the metallic nano-rods in hexagonal configuration to enhance sensitivity of the plasmonic racetrack resonator in sensing application, Plasmonics 12 (4) (2017) 999–1006, https://doi.org/10.1007/s11468-016-0351-x.

[49] M.R. Rakhshani, Tunable and sensitive refractive index sensors by plasmonic absorbers with circular arrays of nanorods and nanotubes for detecting cancerous cells, Plasmonics. 15 (6) (2020) 2071–2080, https://doi.org/10.1007/s11468-020-01237-0.

[50] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, A review on flexible wearables – Recent developments in non-invasive continuous health monitoring, Sens. Actuators Phys. 366 (2024) 114993, https://doi.org/10.1016/j.sna.2023.114993.

[51] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, Smart contact lenses & mdash; a step towards non-invasive continuous eye health monitoring, Biosensors 13 (10) (2023) 933. https://www.mdpi.com/2079-6374/13/10/933.

[52] D. Lo Presti, F. Santucci, C. Massaroni, D. Formica, R. Setola, E. Schena, A multi-point heart rate monitoring using a soft wearable system based on fiber optic technology, Sci. Rep. 11 (1) (2021) 21162, https://doi.org/10.1038/s41598-021-00574-2.

[53] N.L. Kazanskiy, M.A. Butt, S.N. Khonina, Recent advances in wearable optical sensor automation powered by battery versus skin-like battery-free devices for personal healthcare-a review, Nanomaterials 12 (3) (2022) 334. https://www.mdpi.com/2079-4991/12/3/334.

[54] Butt, M.A., Kazanskiy, N.L., Khonina, S.N., 'Revolution in flexible wearable electronics for temperature and pressure monitoring—a review', *Electronics. (Basel)*, 11, 5, 716.

[55] N.L. Kazanskiy, S.N. Khonina, M.A. Butt, Metasurfaces: shaping the future of photonics, Sci. Bull. (2024), https://doi.org/10.1016/j.scib.2024.04.056.

[56] M.S. Bin-Alam, Ultra-high-Q resonances in plasmonic metasurfaces, Nat. Commun. 12 (1) (2021) 974, https://doi.org/10.1038/s41467-021-21196-2.

[57] S.N. Khonina, M.A. Butt, N.L. Kazanskiy, Numerical investigation of metasurface narrowband perfect absorber and a plasmonic sensor for a near-infrared wavelength range, J. Opt. 23 (6) (2021) 065102, https://doi.org/10.1088/2040-8986/abf890.

[58] Wang, Q., Chen, Y., Mao, J., Yang, F., Wang, N., metasurface-assisted terahertz sensing, Sensors 23(13) (2023) 5902. https://www.mdpi.com/1424-8220/23/13/5902.

[59] M.A. Butt, N.L. Kazansky, Narrowband perfect metasurface absorber based on impedance matching, Photonics Lett. Pol. 12 (3) (2020), https://doi.org/10.4302/plp.v12i3.1041.

[60] H. Cheng, Z. Liu, S. Chen, J. Tian, Emergent functionality and controllability in few-layer metasurfaces, Adv. Mater. 27 (36) (2015) 5410–5421, https://doi.org/10.1002/adma.201501506.

[61] J. Milvich, D. Kohler, W. Freude, C. Koos, Integrated phase-sensitive photonic sensors: a system design tutorial, Adv. Opt. Photonics 13 (3) (2021) 584–642.

[62] L. Chrostowski, Silicon photonic resonator sensors and devices, in: Laser Resonators, Microresonators, and Beam Control XIV, SPIE, 2012, pp. 387–402, https://doi.org/10.1117/12.916860.

[63] Y.-L. Chou, A U-shaped optical fiber temperature sensor coated with electrospinning polyvinyl alcohol nanofibers: simulation and experiment, Polymers. (Basel) 14 (10) (2022), https://doi.org/10.3390/polym14102110.

[64] J.H.T. Chan, D. Tang, J. Williamson, H. Martin, A.J. Henning, X. Jiang, An ultra-compact metasurface-based chromatic confocal sensor, CIRP Ann. 72 (1) (2023) 465–468, https://doi.org/10.1016/j.cirp.2023.04.002.

[65] N. Alugubelli, H. Abuissa, A. Roka, Wearable devices for remote monitoring of heart rate and heart rate variability—what we know and what is coming, Sensors 22 (22) (2022), https://doi.org/10.3390/s22228903.

[66] X. Cui, Flexible and breathable all-nanofiber iontronic pressure sensors with ultraviolet shielding and antibacterial performances for wearable electronics, Nano Energy 95 (2022) 107022, https://doi.org/10.1016/j.nanoen.2022.107022.

[67] S. Grego, A. Huffman, M. Lueck, B.R. Stoner, J. Lannon, Nanoimprint lithography fabrication of waveguide-integrated optical gratings with inexpensive stamps, Microelectron. Eng. 87 (10) (2010) 1846–1851, https://doi.org/10.1016/j.mee.2009.11.003.

[68] E. Kilicaslan, M.A. Butt, A. Kazmierczak, R. Piramidowicz, Technological challenges in the development of silica-titania platform for integrated optics, Photonics Lett. Pol. 15 (3) (2023), https://doi.org/10.4302/plp.v15i3.1221.

[69] M.A. Butt, Optical thin films fabrication techniques—towards a low-cost solution for the integrated photonic platform: a review of the current status, Materials 15 (13) (2022) 4591.

[70] M.A. Butt, Thin-Film coating methods: a successful marriage of high-quality and cost-effectiveness—a brief exploration, Coatings 12 (8) (2022) 1115.

[71] M.A. Uddin, H.P. Chan, 8 - Adhesive technology for photonics, in: M.O. Alam, C. Bailey (Eds.), Advanced Adhesives in Electronics, Woodhead Publishing, 2011, pp. 214–258, https://doi.org/10.1533/9780857092892.2.214. Eds.Woodhead Publishing Series in Electronic and Optical Materials.

[72] V. Artel, Wafer bonding techniques for hybrid silicon photonic devices based on surface modifications, in: 2012 14th International Conference on Transparent Optical Networks (ICTON), 2012, pp. 1–4, https://doi.org/10.1109/ICTON.2012.6254462.

[73] G. Alagappan, J.R. Ong, Z. Yang, T.Y.L. Ang, W. Zhao, Y. Jiang, W. Zhang, C. E. Png, Leveraging ai in photonics and beyond, Photonics 9 (2) (2022) 75. https://www.mdpi.com/2304-6732/9/2/75.

[74] J. Zeb Hassan, A. Raza, Z.U.D. Babar, U. Qumar, N. Tolbert Kaner, A. Cassinese, 2D material-based sensing devices: an update, J. Mater. Chem. A 11 (12) (2023) 6016–6063, https://doi.org/10.1039/D2TA07653E.

[75] R. Bogue, Quantum dots: a bright future for photonic nanosensors, Sens. Rev. 30 (4) (2010) 279–284, https://doi.org/10.1108/02602281011072143.