# Advances in Photonic Sensing Technologies: From Crystals to Wearables

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**ABSTRACT**

Photonic sensing devices exploit light–matter interactions to deliver non-invasive, real-time, and highly precise detection of physical, chemical, and biological parameters, underpinning applications in healthcare, environmental monitoring, telecommunications, industrial process control, and structural health monitoring. This review synthesises recent technological and material advances across major photonic sensor classes, including photonic crystal (including photonic crystal fibre sensors, surface plasmon resonance (SPR) sensors, optical fibre-based sensors, and wearable photonic devices, with an emphasis on strategies that improve sensitivity, specificity, flexibility, miniaturisation, multiplexing, and system integration. Using a literature-based comparative analysis of operating principles, device architectures, fabrication routes, and application demonstrations, we highlight how photonic bandgap engineering and defect states enable strong photon confinement (with nanocavity Q-factors reported up to ~38,500), while optofluidic integration supports compact, multifunctional sensing (e.g., 3D photonic crystals in microfluidic channels resolving refractive-index changes of ~6×10^-3). For SPR, prism-coupled (Kretschmann/Otto) and emerging grating-, fibre-, and waveguide-based configurations have been advanced by nanostructured materials and 2D layers; performance gains include gold–graphene hybrids reaching ~350 nm/RIU and architectures targeting high-resolution biosensing (e.g. malaria and HIV DNA hybridisation studies using black phosphorus or $MoS_2/Si_3N_4$ designs). Optical fibre sensors, including intensity-, interferometric-, and grating-based sensors (FBG), are progressing via specialty fibres (tapered, anti-resonant hollow-core, polymer fibres), composite embedding, and hybrid modalities, enabling distributed, EMI-immune monitoring, and AI/IoT-enabled predictive maintenance. Wearable photonic sensors leverage flexible polymers, hydrogels, and nanomaterials (including MXenes) for skin-conformal monitoring. Machine learning (e.g. CycleGAN) can mitigate motion artefacts without accelerometers while improving energy efficiency by approximately 45%. Key barriers include the need for scalable, uniform, and cost-effective manufacturing; long-term stability, reproducibility, and cross-sensitivity; power management; and, for clinical translation, standardization, data privacy, and security. Overall, converging advances in materials, nanostructures, and machine learning are positioning multifunctional, flexible, and spectrally tunable photonic sensors—including emerging bound-state-in-the-continuum concepts—for impactful deployment in precision healthcare, sustainable environmental sensing, and resilient industrial infrastructure.

**Keywords:** Photonic sensing devices, Photonic crystals, Surface plasmon resonance, Optical fibre sensors, Wearable photonic devices, Photonic bandgap engineering, Optofluidic integration.

## A. Introduction

**a. Background on photonic sensing devices:** Photonic sensing devices utilise the interaction between light and matter to detect physical, chemical, or biological parameters with high sensitivity and specificity, making them indispensable in fields such as healthcare, environmental monitoring, telecommunications, and industrial process control. Photonic sensors are crucial because of their noninvasive, real-time, and highly precise detection capabilities, which enable applications ranging from wearable health monitors to environmental pollutant detection and advanced telecommunications [1].

The key principles underpinning photonic sensors include:

I. **Photonic crystals:** These materials have periodic dielectric structures that affect the motion of photons, creating photonic band gaps that control light propagation. Photonic crystals are employed in sensors to enhance optical signals and selectively filter wavelengths, thereby improving sensitivity and specificity. They are foundational in bioinspired colour-tuning devices that dynamically modulate optical properties for sensing applications [2], [3].

II. **Surface Plasmon Resonance (SPR):** SPR exploits the resonant oscillation of electrons at the interface between ametalanddielectric,which is triggered by incident light. This phenomenon is highly sensitive to changes in the refractive index near the surface, making SPR a powerful principle for biosensing and chemical detection applications. This enables label-free, real-time monitoring of molecular interactions without direct contact with the analyte [4].

III. **Optical fibres:** Optical fibre sensors rely on the transmission and modulation of light through flexible fibres, allowing remote and in situ sensing in challenging environments. Advances in optical fibre technology have led to the development of multifunctional sensors capable of detecting various physical and biochemical parameters. These sensors can be integrated into medical instruments (catheters, needles, and endoscopes) and wearable devices for continuous health monitoring, highlighting their versatility and importance [1], [5].

Recent advancements in photonic sensing have involved the development of flexible, bioinspired, and multifunctional materials that enable dynamic structural-colour tuning and enhanced sensing performance. Breakthroughs in silicon photonics and mid-infrared photonic sensors have expanded the capabilities of telecommunications, biosensing, and environmental applications. Wearable photonic sensors are transforming healthcare by providing portable, noninvasive devices for personalised medicine, incorporating optical fibres and novel photonic materials [1], [2], [6], [7].

The market demand for photonic sensors is rapidly growing owing to their broad applicability, improved fabrication techniques, and integration with flexible and wearable platforms. Their unique advantages in sensitivity, specificity, and real-time monitoring position photonic sensors as key components in advancing personalised healthcare, environmental sustainability, and next-generation communication systems [1], [8].

Photonic sensing devices harness principles such as photonic crystals, surface plasmon resonance, and optical fibre technologies to deliver high-performance and versatile sensing solutions. Ongoing innovations continue to expand their application scope and commercial viability, meeting the escalating global demand for precise and real-time sensing technologies.

**b. Objectives of the review:** This review outlines and analyzes the main types of photonic sensors, including wearable, mid-infrared, photonic crystal, flexible and stretchable, and optical fibre-based biomedical photonic sensors. Each category is examined with respect to recent technological developments, material innovations, and advances in sensor architectures that enhance performance characteristics, such as sensitivity, specificity, flexibility, and integration capabilities [1], [5], [7], [9], [10].

The purpose of reviewing these recent developments is to provide a comprehensive understanding of how cutting-edge innovations in photonic sensing mechanisms and materials drive performance improvements and expand application domains. Emphasis will be placed on strategies that optimise sensor design, material selection, and fabrication techniques for real-world applicability in healthcare, environmental monitoring, telecommunications, and industrial processes. This evaluation aims to identify critical technological challenges and highlight promising research trajectories that could further enhance the functionality and usability of sensors [1], [7], [9].

Furthermore, this review focuses on applications and future prospects by discussing the translational potential of these photonic sensors. It explores how innovations in sensor flexibility, miniaturisation, and multiplexing capabilities are opening new frontiers in personalised healthcare, wearable technologies, precision diagnostics, and sustainable environmental monitoring. The outlook section anticipates emerging trends and challenges, including integration with digital platforms and energy management, which will shape the next generation of photonic sensing devices [1], [5], [10].

**B. Photonic Crystal-Based Sensing Devices**

**a. Fundamental principles:** Photonic bandgaps are ranges of wavelengths in which light propagation through a photonic crystal is forbidden owing to the periodic modulation of the refractive index within the crystal structure. This property is analogous to the electronic bandgaps in semiconductors but applies to photons. The presence of photonic bandgaps allows photonic crystals to confine and control light with high precision, making them essential for photon manipulation in optical circuits and sensing applications. For instance, three-dimensional (3D) photonic crystals can create complete photonic bandgaps that block light propagation in all directions, enabling highly efficient light confinement and manipulation for sensing with reduced losses and enhanced light-matter interaction [11], [12], [13].

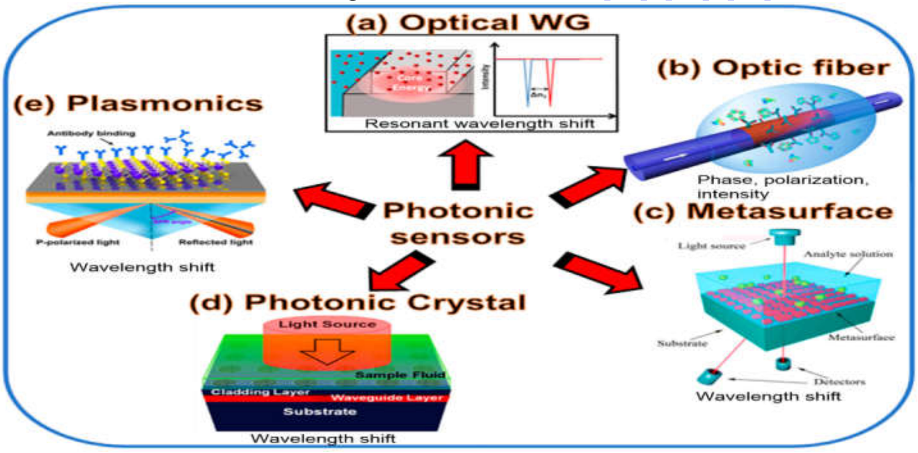


Fig.1 Photonic Sensors

Various photonic crystal structures have been developed for sensor integration, primarily one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures. Two-dimensional photonic crystals often take the form of planar waveguides with periodic lattices that exhibit polarisation-sensitive photonic bandgaps suitable for near-infrared optical sensing. Their planar geometry allows for easier integration with other optoelectronic components [14]. Three-dimensional photonic crystals provide complete photonic bandgaps and superior photon confinement, leading to very high-quality optical resonators with quality factors (Q-factors) as high as ~38,500 in nanocavities for enhanced sensing precision [12]. Photonic crystal fibres, another important class, employ periodic structures in the fibre cladding to create photonic bandgaps that guide light through hollow cores, enhancing the sensitivity for biochemical and environmental sensing applications, as shown in Fig. 1 [9], [15].

The key parameters influencing the photonic crystal sensor performance include:

I. **Quality factor (Q-factor):** Indicates the sharpness of the resonant mode and the energy confinement time within the cavity or defect region. Higher Q-factors signify lower energy losses and greater sensitivity, as even small perturbations in the refractive index or the presence of analytes cause measurable shifts in the resonance frequency [11], [12].

II. **Sensitivity:** Refers to the ability of the sensor to detect minute changes in the environment, such as changes in the refractive index, gas concentration, or biochemical binding. Photonic crystals achieve enhanced sensitivity by exploiting localised defect states within the bandgap or by employing surface states that enable strong light-matter interactions [11], [16].

III. **Compactness and Integration:** The geometric design—such as waveguides, cavities, or fibers—affects the device footprint an multi-wavelengths operation capabilities, which are crucial miniaturized, multiplexed sensing platforms [9].

IV. **Defect engineering:** The introduction of intentional defects creates localised photonic states within the bandgap that can be finely tuned for specific sensing functionalities, enhancing selectivity and resolution [17].

Thus, photonic crystals engineered with precise periodicity and defect structures serve as highly sensitive platforms for optical sensing, where the control of photonic bandgaps enables effective light manipulation and superior sensor performance, marked by high Q-factors and sensitivity.

**b. Recent advancements:** Recent advancements in photonic crystal sensors have focused substantially on novel designs that enhance sensitivity, integration with complementary technologies such as microfluidics, and the expansion of specific application domains, including biosensing and gas detection. Recent photonic crystal biosensors leverage configurations such as 1D photonic crystals, slabs, waveguides, and microcavities to achieve high sensitivity and low detection limits. Their low-cost mass fabrication and compact design further promote their use in medical and environmental sensors [18].

A key development is the integration of photonic crystals with microfluidic platforms, which enables the development of highly compact and multifunctional sensor devices. For example, three-dimensional photonic crystals fabricated within microfluidic channels can detect minute refractive index changes (~6×10^-3), proving useful for fluid sensing. The ability to couple microfluidics with photonic crystals allows for the precise control of fluid samples for real-time analysis and enhances sensitivity by confining analytes and light interaction in miniaturised volumes (Fig. 2) [19], [20].

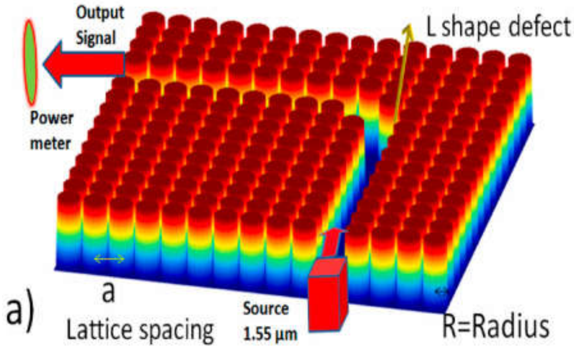


Fig.2 Recent Progress in photonic crystal device

Beyond integration, advances in femtosecond laser fabrication have enabled the development of monolithic microfluidic sensors on glass substrates, allowing the incorporation of optofluidic and electrofluidic functionalities for chemical and biological applications. These fabrication methods support the creation of complex 3D architectures tailored for enhanced light-sample interactions and multiplex sensing [21]. Moreover, the integration of photodetectors with lab-on-chip digital microfluidic systems has been realised, opening pathways for miniaturised, automated diagnostic platforms with improved optical sensing capabilities [22].

Specific application examples highlight photonic crystal nanobeam cavities, which provide ultra-small, flexible on-chip sensing platforms for refractive index detection, nanoparticle sensing, optomechanics, and temperature monitoring. The excellent light confinement in these structures translates to enhanced sensor performance in biomedical diagnostics and environmental monitoring applications [23]. Photonic crystal fibres also serve as versatile chemical sensors and microreactors, utilising tight light confinement for quantitative analysis and photochemical reactions, which are relevant in the gas and liquid sensing domains [24].

Recent advancements in photonic crystal sensors have focused on sophisticated designs for sensitivity enhancement, seamless integration with microfluidic systems for miniaturisation and multifunctionality, and demonstrated applications in biosensing and gas detection. These developments have collectively advanced the performance, reliability, and practical usability of photonic crystal-based sensors in diverse real-world scenarios.

**c. Challenges and future directions:** Current challenges in photonic sensor fabrication and scalability include difficulties in working with rigid materials and substrates, which limit the application of sensors in flexible or deformable environments, such as wearable devices and soft robotics. Conventional fabrication methods may lack uniformity and are often incompatible with scale-up production, especially for materials such as perovskites and nanomaterials, which require precise control over stability and uniformity. Furthermore, scalable manufacturing methods that maintain high precision while being cost-effective remain critical barriers [10], [25], [26].

Potential improvements in sensor sensitivity and selectivity are being pursued through advanced material design, structural innovation, and signal processing techniques. Enhancing sensor-analyte interactions via flexible and deformable structural colour materials and integrating soft polymers can significantly increase sensitivity. Additionally, machine learning techniques have been employed to refine selectivity by compensating for baseline drift and environmental interference. The incorporation of novel nanomaterials, hybrid composites, and doping strategies further improves the performance by increasing the interaction sites and tailoring the sensor responses [27], [28], [29], [30].

Emerging applications encompass smart wearable devices, flexible and stretchable sensors for physiological monitoring, and intelligent gas-sensing platforms focused on environmental sustainability and public health. Nanophotonic sensors are connected with fields such as quantum technologies, machine learning, and integrated photonics to enable enhanced detection schemes, programmability, and miniaturisation. Furthermore, interdisciplinary research is advancing innovations in optical-electrical dual-signal sensors, high-throughput screening, and real-time diagnostics, creating avenues for sensors in healthcare, environmental monitoring, and industrial automation. Future research aims to develop green manufacturing processes to align sensor production with environmental awareness [1], [10], [25], [29], [30].

In summary, although significant progress has been made in photonic sensor technology, key challenges remain in terms of scalable, uniform fabrication and enhanced functional performance. Ongoing advances in materials science, integration strategies, and computational methods herald promising future directions with wide-ranging applications, from personalised medicine to environmental sensing and beyond.

**C. Surface Plasmon Resonance (SPR) Based Sensing Devices**

**a. Working principle of SPR sensors:** Surface plasmon resonance (SPR) sensors operate based on the excitation of surface plasmons, which are coherent oscillations of free electrons at the interface between a metal and a dielectric, typically occurring at optical frequencies. When p-polarised light strikes this interface under specific resonance conditions, energy is transferred to the surface plasmons, resulting in a characteristic dip in the reflected light intensity. The resonance condition depends sensitively on the refractive index near the metal surface, making SPR sensors highly effective for detecting molecular binding events and changes in the surrounding medium [31], [32].

The Kretschmann and Otto configurations are commonly used to excite surface plasmons. In the Kretschmann setup, a thin metal film is deposited on a glass prism and illuminated internally; the evanescent field generated by total internal reflection excites the surface plasmons at the metal-dielectric interface. The Otto configuration involves a prism separated by a small gap from a metal surface, where the evanescent wave tunnels through the gap to excite the plasmons. Both configurations enable the resonance to be tuned by changing the angle of incidence or wavelength, facilitating the sensitive detection of refractive index changes near the sensor surface [33].

Key performance metrics of SPR sensors include sensitivity, which quantifies the shift in resonance angle or wavelength per unit change in the refractive index (e.g. degrees/RIU or nm/RIU), and resolution, which is the sensor's ability to discern small changes in the refractive index or analyte concentration. Higher sensitivity corresponds to larger resonance shifts, which improves the detection limit. The resolution is affected by factors such as the resonance peak width and signal-to-noise ratio. For instance, gold-graphene hybrid nanostructures have demonstrated sensitivities of 350 nm/RIU with enhanced figures of merit, while gratings and nano-grating SPR sensors achieve sharp resonance peaks that significantly improve sensor resolution and sensitivity [34], [35], [36]. Moreover, recent sensor designs incorporating materials such as black phosphorus and molybdenum disulfide have optimised sensitivity and detection accuracy for biosensing applications, such as malaria and HIV DNA hybridisation detection (Fig. 3) [37], [38].

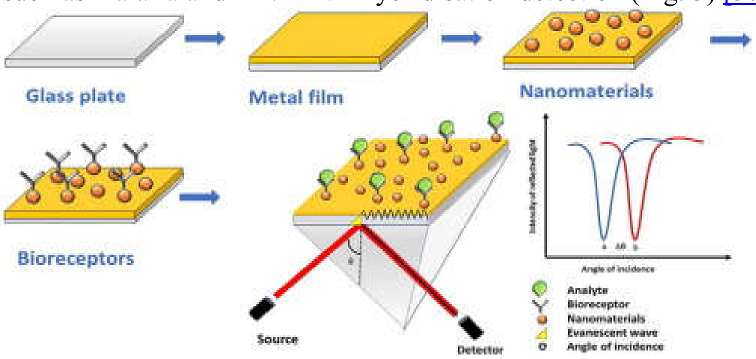


Fig 3 Mechanism of Surface plasmon resonance (SPR) sensors

In summary, SPR sensors function by exploiting surface plasmon excitation at metal-dielectric interfaces under carefully controlled optical conditions, with Kretschmann and Otto configurations being the predominant excitation configurations. Their performance is characterised mainly by sensitivity and resolution, which have been enhanced through novel nanomaterials, gratings, and hybrid structures, pushing SPR sensors toward higher precision and practical implementation in biosensing and chemical detection applications.

**b. Recent developments:** Recent developments in surface plasmon resonance (SPR) sensors have been significantly driven by advances in nanostructured plasmonic materials. Nanofabrication technologies have enabled the creation of plasmonic nanoarrays and patterned nanostructures that offer ultrasensitive detection capabilities in chemical and biological analyses. Notably, nanomaterials, such as silver and carbon-based materials, including graphene, graphene oxide, and carbon nanotubes, have played crucial roles in enhancing sensor performance. These materials provide high surface areas, tunable optical properties, and improved biomolecule compatibility, thereby increasing the sensitivity and specificity of SPR sensors [39], [40], [41].

The integration of SPR with other sensing modalities, particularly microfluidics, has propelled the development of compact, high-throughput biosensing platforms. Microfluidic chips combined with plasmonic nanostructure arrays facilitate the multiplex detection of multiple analytes simultaneously under real-time and label-free conditions. Furthermore, coupling SPR with electrochemical sensing and surface-enhanced Raman scattering (SERS) techniques has broadened its applications and improved its accuracy and detection limits. These hybrid systems are advantageous for biomedical studies and point-of-care diagnostics, accelerating rapid and sensitive molecular analyses with minimised sample volumes [39], [42], [43].

The novel applications of SPR in chemical and biological sensing continue to expand. These sensors are widely employed for biomolecular interaction analysis, medical diagnostics, such as cancer biomarker and pathogen detection, environmental toxin monitoring, and food safety assessments. Innovations in sensor architecture include grating-based, fibre-optic, and waveguide-modulated SPR sensors, which enhance their compatibility with diverse analytical scenarios. Research efforts have focused on improving sensitivity through novel surface coatings, sensing media, and immobilisation techniques, which improve selectivity and reduce false detections. The breadth of applications reflects the transformative impact of SPR technology in real-time, label-free biomolecular detection and its evolving role in precision healthcare and environmental monitoring [44], [45], [46].

Collectively, these advancements highlight significant strides in nanostructured materials, integrated sensing platforms, and broadened practical applications, reinforcing SPR sensors as versatility and power tools in contemporary chemical and biological analytics.

**c. Challenges and future prospects:** Surface plasmon resonance (SPR) sensors face challenges related to stability and reproducibility, particularly due to nonspecific adsorption, degradation of biomolecular activity over time, and variability in surface modifications. Strategies such as improved sensor surface design, advanced immobilisation techniques, and incorporation of novel materials such as 2D nanomaterials and gold nanostructures have been developed to enhance sensor stability and reduce operational variability, which are essential for reliable detection in complex biological and chemical environments [46], [47].

Miniaturisation and integration with portable devices remain key objectives for enabling on-site point-of-care diagnostics. Conventional SPR sensors typically involve bulky prism-coupled systems that limit portability. Recent advances include plasmonic gratings, fibre-optic SPR sensors, and phase-interrogation methods optimised for lab-on-a-chip platforms, which offer compactness, lower sample volume requirements, and improved ease of use. These innovations have progressed toward practical, handheld SPR sensing devices capable of high sensitivity and rapid response, suitable for field applications [48], [49], [50].

SPR sensors also show great potential for real-time, label-free sensing in complex environments, enabling the dynamic monitoring of biomolecular interactions without the need for fluorescent or radioactive labels. However, the ability to differentiate specific signals from background interference remains challenging, particularly in heterogeneous biological sample. The integration of SPR imaging (SPRi) and multiplexed sensor arrays improves discrimination and throughput. Continued improvements in nanostructure design, surface coatings, and advanced interrogation methods, such as phase-sensitive detection, contribute to enhanced sensor selectivity and temporal resolution in complex matrices [46], [50], [51].

In conclusion, addressing stability and reproducibility challenges through surface engineering, achieving miniaturisation combined with portable integration, and exploiting real-time, label-free sensing capabilities represent the forefront of SPR sensor development, promising impactful applications in healthcare and environmental monitoring.

**D. Optical Fiber-Based Sensing Devices**

**a.** Optical fibre sensors are devices that utilise optical fibres to detect changes in physical, chemical, or biological parameters by monitoring the modifications in the properties of light transmitted through or reflected from the fibre. Key types of optical fibres used in sensing include single-mode fibres, which support one propagation mode and thus offer high spatial resolution and low dispersion, and multimode fibres, which support multiple propagation modes and are typically used when a higher light collection efficiency or simpler coupling is required. Polymer optical fibers (POFs) are also notable for their flexibility and high strain tolerance [52], [53].

The sensing mechanisms of optical fibre sensors can be broadly categorised into intensity-based, interferometric, and grating-based mechanisms. Intensity-based sensors monitor changes in light intensity caused by variations in absorption, scattering, or bend loss. Interferometric sensors rely on the interference of two or more light beams travelling along different optical paths to detect phase shifts induced by environmental changes. Grating-based sensors, such as fibre Bragg gratings (FBGs), reflect specific wavelengths of light which shift in response to strain or temperature changes, providing high sensitivity and wavelength-encoded sensing [52], [54], [55].

Optical fibre sensors offer several advantages over traditional electronic sensors. They enable distributed sensing along the fibre length, allowing spatially resolved measurements over long distances to be performed. They exhibit immunity to electromagnetic interference (EMI), making them suitable for harsh environments and applications near powerful electrical equipment. Additionally, they are small, lightweight, flexible, and capable of remote sensing in inaccessible or hazardous areas. The passive nature and low attenuation of optical fibres enhance sensor stability and enable multiplexing for simultaneous multi-parameter detection, as shown in Fig. 4 [56], [57], [58].

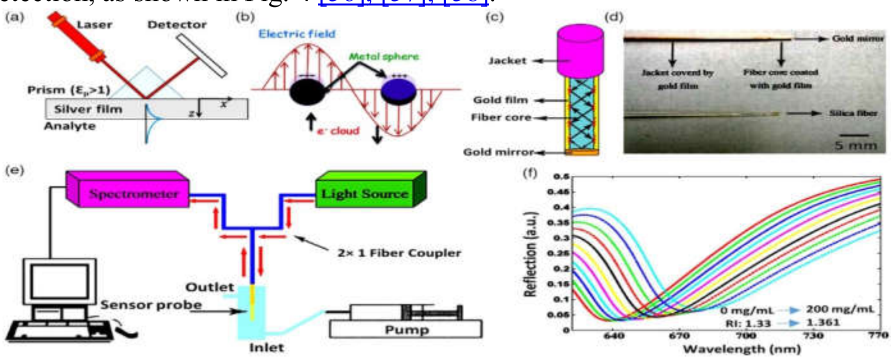

Fig.4 working of optical fiber sensor

In summary, optical fibre sensors leverage distinct fibre types and diverse sensing mechanisms to provide highly sensitive, flexible, and reliable detection solutions for various applications. Their advantages in distributed sensing, EMI immunity, and remote operability position them as indispensable tools in military, industrial, environmental, and biomedical fields.

**b. Recent advancements:** Recent advancements in optical fibre sensors have focused heavily on developing specialty fibres designed to enhance their sensing capabilities. These include tapered optical fibres that offer improved sensitivity and real-time monitoring, anti-resonant hollow-core fibres that provide ultra-compact designs and large measurement ranges, and polymer optical fibres (POFs) which enable high flexibility, strain tolerance, and large deformation sensing. Specialty fibres have broadened the application potential of optical fibre sensors in biosensing, environmental monitoring, and industrial surveillance [59], [60], [61].

The integration of functional materials with optical fibres has expanded the functionalities of sensors and the scope of target detection. This includes embedding fibre Bragg gratings (FBGs) into composite materials for structural health monitoring (SHM) and hybrid sensor systems combining scattering, interferometric, and polarimetric methods to yield comprehensive monitoring solutions, particularly in aerospace and civil infrastructure. Functionalization enables multiplexing, improved specificity, and enhanced durability in complex environments [62], [63].

Novel applications are increasingly being demonstrated in the structural health monitoring of critical infrastructure, such as bridges, tunnels, pipelines, and high-rise buildings, where optical fibre sensors provide continuous, distributed, and real-time data collection with immunity to electromagnetic interference. Environmental sensing applications encompass the high-resolution and reliable monitoring of strain, temperature, chemical composition, and damage detection. The integration of artificial intelligence (AI) and Internet of Things (IoT) platforms further enables predictive maintenance and intelligent data analytics for resilient urban infrastructure [64], [65], [66].

Collectively, these advancements signal a progressive shift toward highly sensitive, flexible, and multifunctional optical fibre sensors tailored for diverse and expanding critical sensing challenges in the structural health and environmental domains.

**c. Challenges and future directions:** Optical fibre sensors face challenges in improving their long-term stability and reliability owing to environmental degradation, signal attenuation, and component aging. Ensuring consistent sensor operation over extended periods requires advanced materials, robust sensor packaging, and self-compensation techniques for environmental fluctuations [67].

Cross-sensitivity, in which sensors respond to multiple environmental factors, such as temperature, humidity, and pressure, simultaneously, remains a critical issue that affects measurement accuracy. Addressing this requires sensor designs that incorporate compensation channels or multiparameter self-referencing approaches. For example, multi-core fibres integrated with surface plasmon resonance and fibre Bragg grating elements have been developed to independently measure variables and correct for cross-interference [68], [69].

Looking forward, the potential for multiparameter sensing and the development of smart sensor networks represent key future directions. Advances in multiplexing techniques, distributed sensing, and integration with machine learning/artificial intelligence have enabled the real-time analysis of complex sensor data streams for structural health monitoring, environmental sensing, and industrial process control. These sensor networks offer enhanced spatial coverage, predictive maintenance capabilities, and adaptive responses in challenging environments [67], [70], [71].

In summary, overcoming long-term stability concerns, mitigating cross-sensitivity effects via innovative multiparameter designs, and harnessing smart networked sensing platforms with AI-driven data analytics are crucial pathways to realise the full potential of optical fibre sensor technologies in diverse applications [67], [72], [73].

**E. Optical Wearable Sensors**

**a. Overview of wearable photonic sensors:** Wearable photonic sensors employ light-based mechanisms to monitor physiological parameters in real time with high sensitivity and noninvasiveness. Common types of wearable optical sensors include reflectance-based sensors that measure changes in the intensity or spectrum of light reflected from the skin or tissues and fluorescence-based sensors that detect light emitted from fluorophores in response to target biomolecules. These sensing modalities enable the monitoring of vital signs, biochemical markers, and other physiological variables [74], [75].

The integration of photonic components with flexible substrates is a critical enabling technology for wearability. Flexible and stretchable materials, such as polymers and hydrogels, are used as substrates to conform intimately to the skin and soft tissues. Photonic nanomaterials and bioinspired photonic structures are embedded within these flexible matrices, retaining optical functionality while allowing bending, stretching, and twisting without performance degradation. This facilitates continuous monitoring during dynamic body movements and supports conformal and comfortable wearing (Fig. 5) [8], [10], [76].

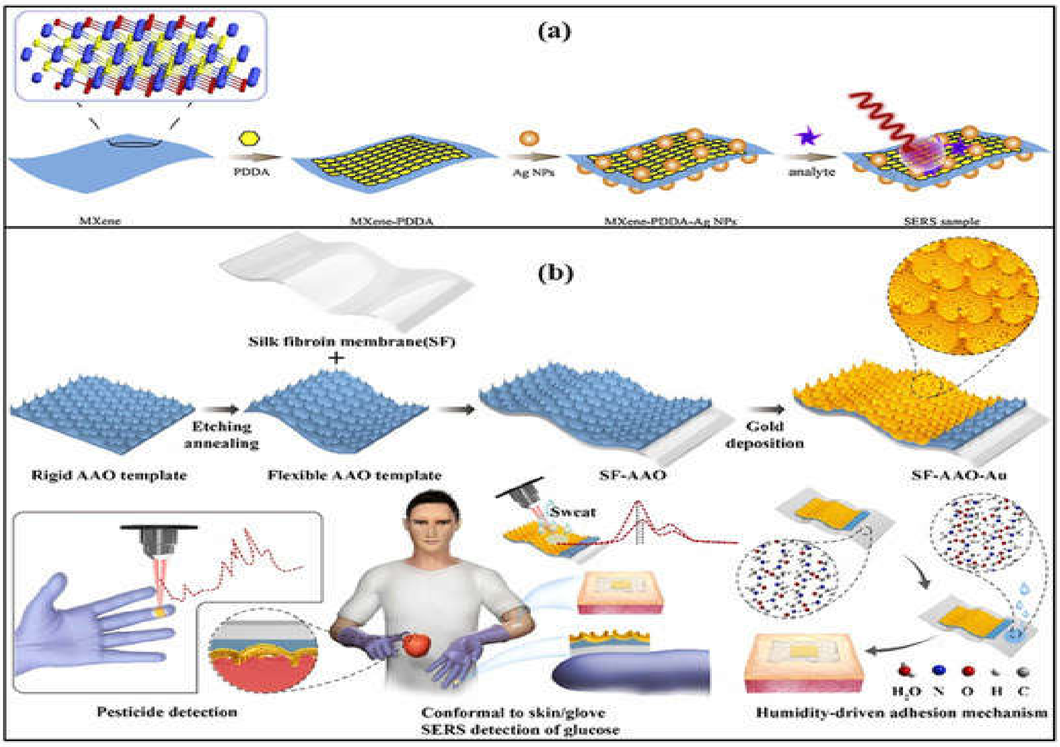


Fig 5. **Optical Wearable Sensors**

Key design considerations for wearability and comfort include material biocompatibility, mechanical flexibility, breathability, and lightweight construction to reduce skin irritation and ensure long-term use. The device form factors should balance the sensor sensitivity and durability while minimising the bulk and stiffness. Strategies such as incorporating microscale patterning, surface bonding, and integration of power and wireless communication modules are also important for functional and user-friendly wearable photonic systems suitable for continuous health monitoring and diagnostics [77], [78], [79].

Together, these aspects underpin the development of next-generation wearable photonic sensors that offer sensitive, real-time physiological monitoring with maximal comfort and usability for personalised healthcare applications [10], [74], [76].

**b. Recent advancements:** Recent advancements in wearable optical sensors have been marked by the development of skin-interfaced devices that achieve an intimate and stable coupling with the human body. Hydrogels with high transparency, softness, stretchability, and biocompatibility have emerged as critical materials for skin-conformal wearable electronics. These materials provide mechanical resilience and ion-based conductivity, enhancing sensor stability and user comfort during dynamic motion [80].

Novel materials, such as conducting nanocomposite hydrogels and two-dimensional materials, including MXenes, have been engineered to improve the flexibility, durability, and biocompatibility of sensors. These materials confer properties such as self-healing, biodegradability, high electrical conductivity, and tunable architectures, thereby expanding the applicability of wearable sensors in diverse physiological monitoring contexts [81], [82].

Applications have expanded to include continuous health monitoring of vital signs and biochemical analytes, real-time sweat analysis of biomarkers, and fitness tracking. Wearable optical sensors employing diverse mechanisms, such as surface-enhanced Raman scattering, fluorescence, plasmonics, and photoplethysmography, provide high sensitivity and specificity. They support functionalities ranging from cardiovascular and respiratory monitoring to hydration and metabolic status tracking, offering noninvasive, real-time health management tools with the potential for early disease detection and personalised healthcare [83], [84], [85].

In summary, advances in skin-interfaced device architectures, innovative biocompatible materials, and expanding application domains underpin the rapidly evolving landscape of wearable optical sensors for continuous health monitoring and fitness tracking.

**c. Challenges and future directions:** Wearable optical sensors face significant challenges related to motion artefacts and environmental interference, which can cause signal distortion and reduce measurement accuracy. Conventional approaches often rely on additional accelerometers for artefact removal; however, these increase power consumption and device complexity. Recent advances include machine learning-based algorithms, such as CycleGAN, which enable accurate motion artefact removal without extra sensors, enhancing data quality and improving energy efficiency by approximately 45% [86]. This advancement is critical for enabling reliable monitoring of daily activities and dynamic conditions.

Improving power efficiency and battery life is critical for wearable optical sensors to achieve prolonged and user-friendly operation. Flexible electronics and novel material systems are being developed to reduce power requirements while maintaining high sensitivities. Efficient design strategies involve combining low-power photonic components with optimised signal processing and energy-harvesting technologies, facilitating continuous monitoring without frequent recharging or replacement [1], [87].Looking forward, wearable optical sensors hold significant potential for personalised medicine and preventive healthcare. They enable real-time, noninvasive monitoring of physiological and biochemical parameters, informing early diagnosis, disease management, and health optimisation. The integration of AI and big data analytics facilitates the development of predictive healthcare models that can be customised to individual patients, thereby transforming traditional reactive medicine into a proactive, tailored approach [1], [88], [89].

In summary, addressing motion artefacts through advanced algorithms, enhancing power efficiency via material and system innovations, and leveraging wearable sensors for personalised preventive healthcare applications are pivotal for advancing wearable optical sensor technologies [1], [86], [88].

## F. Conclusion

Photonic sensors have seen substantial advancements in multiple categories, including photonic crystal-based sensors, surface plasmon resonance (SPR) sensors, optical fibre sensors, optical waveguide-based sensors, and wearable photonic devices. Each category has enhanced sensitivity, precision, and multiplexing capabilities essential for accurate physical, chemical, and biological measurements. For instance, photonic crystal fibre sensors integrating SPR effects have achieved ultra-broad refractive index detection ranges with sensitivities reaching thousands of nanometres per refractive index unit (RIU), demonstrating both tunability and multi-parameter sensing potential.

Machine learning has emerged as a critical enabler for optimizing optical sensor performance by facilitating accurate predictions of sensor outputs and eliminating the need for complex calculations. This integration has significantly improved the reliability and efficacy of SPR and photonic crystal fibre sensors. Moreover, novel sensor architectures employing multilayer coatings and innovative materials, such as gold nanoshells, have extended spectral tunability from the visible to near- and mid-infrared wavelengths, expanding their applicability in biosensing and chemical detection.

Emerging trends reveal a strong convergence around multifunctional and integrated photonic sensing platforms capable of simultaneous multi-parameter detection (e.g. magnetic fields, temperature, and refractive index), enhancing the applicability of sensors in complex environments. Flexible, wearable photonic sensors have concurrently advanced through novel materials and device designs, enabling skin-interfaced, noninvasive health monitoring with high biocompatibility and user comfort.

Cross-cutting themes include the integration of advanced materials and nanostructures, the use of machine learning for sensor optimisation, the expansion of sensing modalities across spectral ranges, and an emphasis on miniaturisation and flexibility suitable for real-world deployments. These advances collectively indicate highly sensitive, versatile, and adaptive photonic sensor technologies that are positioned to address current and future challenges in healthcare, environmental monitoring, and industrial applications.

**b. Future outlook:** Potential breakthroughs in photonic sensors are expected to significantly impact healthcare, environmental monitoring, and industrial applications. Innovations such as flexible and stretchable photonic sensors capable of conforming to complex surfaces will enable seamless integration into wearable and implantable devices, facilitating continuous real-time monitoring with high sensitivity and selectivity. Advances in machine learning integration with sensing platforms promise enhanced signal processing, artefact removal, and autonomous interpretation of complex sensor data, further improving their accuracy and usability. Furthermore, research on photonic bound states in the continuum (BICs) suggests new opportunities for ultra-high-performance optoelectronic devices that support novel sensing modalities and enhanced detection limits.

Key challenges remain for widespread adoption, including enhancing material robustness and biocomcompatibility, mitigating motion and environmental interferences, and improving power efficiency to enable longer operational lifetimes. Achieving scalable and cost-effective manufacturing methods while maintaining sensor performance and miniaturisation is critical. Developing standardised protocols for integration within healthcare and industrial systems is essential to ensure interoperability, regulatory approval, and user acceptance. Additionally, ethical considerations regarding data privacy and security must be addressed, particularly for wearable and implantable sensor applications.

The prospects for commercialisation are strong, given the growing demand for personalised medicine, preventive healthcare, and smart environments facilitated by the Internet of Things (IoT). Market growth is supported by ongoing technological advances, an expanding translational research landscape, and increasing acceptance of digital health solutions. Close collaboration between materials scientists, device engineers, clinicians, and regulatory bodies will accelerate the translation of laboratory innovations into robust and user-friendly products. The fusion of photonic sensor technology with intelligent data analytics and wireless communication is expected to unlock new applications and enhance patient outcomes, driving broader and more impactful adoption across various sectors.

Photonic sensing technologies have transformative potential across multiple domains, offering unprecedented sensitivity, versatility, and noninvasive measurement capabilities. The integration of these sensors with flexible, skin-compatible materials and advanced nanomaterials enables real-time physiological and environmental monitoring, revolutionising healthcare diagnostics, environmental sensing, and industrial applications. The convergence of photonics with machine learning and data analytics further empowers these sensors to deliver accurate and contextualised information critical for personalised health management and preventive medicine.

Advancements in specialty optical fibres and the integration of functional materials have expanded the sensing modalities, enabling enhanced selectivity, multi-parameter detection, and novel applications such as structural health monitoring and environmental assessment. These developments underscore a growing trend toward multifunctional, flexible, and miniaturised photonic sensors tailored for real-world applications. Addressing persistent challenges, such as motion artefact mitigation, environmental interference compensation, and power efficiency improvement, is essential to fully realise the potential of wearable photonic sensors. In parallel, power management and battery life optimisation remain critical for sustained and user-friendly operation. Overcoming these technical hurdles will facilitate broader adoption in personalised medicine and continuous health monitoring applications.

Interdisciplinary collaboration is paramount to accelerate innovation and translation. Materials scientists, photonics engineers, data scientists, clinicians, and regulatory experts must work synergistically to develop integrated solutions that not only advance sensor performance but also ensure usability, scalability, and regulatory compliance.

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