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Enhancing Sensitivity and Stability in Surface Plasmon Resonance Sensing through Integration with Photonic Crystal Fibers: A Comprehensive Review

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ABSTRACT

Surface Plasmon Resonance (SPR) sensing, bolstered by integration with Photonic Crystal Fibers (PCFs), presents a compelling avenue for advancing sensitivity and stability in optical sensing. This review comprehensively explores recent developments in SPR sensing utilizing PCFs, focusing on enhancing sensitivity and stability. Through an analysis of underlying principles, advantages, and applications, this review elucidates the potential of PCF-based SPR sensing in diverse fields such as biomedicine, environmental monitoring, and industrial analysis. Challenges and future directions in PCF-based SPR sensing are discussed, offering insights into overcoming limitations and driving innovation. This review serves as a valuable resource for researchers and practitioners seeking to leverage PCF-based SPR sensing for enhanced optical sensing capabilities.

INTRODUCTION

Surface Plasmon Resonance (SPR) sensing has emerged as a powerful technique for label-free detection and analysis in various fields, including biochemistry, pharmacology, environmental monitoring, and materials science. By exploiting the interaction between light and a metal-dielectric interface, SPR sensing offers high sensitivity, real-time analysis, and versatility, making it a valuable tool for a wide range of applications. However, traditional SPR sensors face challenges related to sensitivity, stability, and miniaturization, limiting their effectiveness in certain scenarios (1).

In recent years, significant efforts have been made to overcome these limitations by integrating SPR sensing with Photonic Crystal Fibers (PCFs), a novel class of optical fibers with unique properties. PCFs, characterized by a periodic arrangement of air holes in the cladding, offer enhanced light confinement, increased surface interaction, and improved stability compared to conventional optical fibers (2). The integration of PCFs with SPR sensing presents an exciting opportunity to enhance sensitivity and stability while enabling miniaturization and integration, thereby expanding the capabilities of SPR sensing for various applications (3).This review aims to provide a comprehensive overview of the recent advancements in PCF-based SPR sensing, focusing on strategies to enhance sensitivity and stability. We begin by discussing the principles of SPR sensing and the challenges faced by traditional SPR sensors(4). We then introduce the concept of PCFs and highlight their unique optical properties that make them well-suited for integration with SPR sensing. Subsequently, we delve into the integration of PCFs with SPR sensing and explore the advantages that PCFs offer in terms of sensitivity, stability, and miniaturization.

In recent years, the exploration of innovative sensor technologies has become instrumental in advancing various fields. Abdelghaffar and colleagues (5) introduced a novel PCF based SPR sensor dedicated to the precise identification of cancer cells. Utilizing FEM modeling, the sensor featured a unique PCF surface coated with ZrN, incorporating air cavities in a hexagonal pattern. This biosensor exhibited remarkable detection capabilities with Wavelength Sensitivity (WS) values of 6214.28, 3800.00, and 5008.33 nm/RIU for breast, cervical, and basal carcinoma cells, respectively. The integration of optical sensors (OS) in cancer diagnosis presents a direct, cost-efficient, and highly sensitive alternative to traditional methods.

Jabin et al. (6) presented a distinctive single-core SPR-based cancer detector, showcasing enhanced detection capabilities for cells with harmful mutations. The sensor, featuring a titanium layer acting as a barrier, demonstrated an impressive peak WS performance of 17,500 nm/RIU and an AS value ranging from –340 RIU-1 to –420 RIU-1 for different cancer cells. Yasli et al. (7) utilized a PCF sensor with SPR to differentiate between six types of cancer cells, emphasizing the impact of bending on sensor sensitivity, aligning with conclusions from previous studies. Li and collaborators proposed an innovative H-shaped PCF with U-shaped microchannels, serving as an SPR sensor. This configuration, featuring a silver layer with integrated graphene (8), demonstrated a peak WS of 12.6 × 10−3 nm/RIU and an average WS of 2770 nm/RIU within a linear RI detection scale of 1.33–1.36. Mollah et al. (9) focused on cancer cell observation utilizing a PCF sensor with an interferometer (Sagnac), achieving impressive WS values for various cell types. The transmission spectrum generated by the Sagnac interferometer highlighted the distinctive refractive index characteristics of cancerous and normal cells within the fiber. In a novel sensing approach, Liu and team introduced a methodology employing non-corrosive gold (Au) within a double-open-loop system, achieving a maximum WS of 20,000 nm/RIU, AS of 208.21 RIU−1, and a sensor resolution of 5×10−6 RIU. Liu et al. also presented a breakthrough incorporating a lattice-patterned PCF with a layer of indium tin oxide, achieving a peak WS of 60,000 nm/RIU and an average sensitivity of 18,400 nm/RIU within an RI range of 1.380 to 1.405 (10). Furthermore, Chao Liu and their research team (14) introduced an innovative chemical detector using micro structured optical fiber for gas-liquid impurity recognition and RI variations within the infrared spectrum. The detector, integrated into the outer layer of the fiber, demonstrated impressive metrics with a peak WS of 15,000 nm/RIU, AS of 1603.370 RIU−1, and spectral resolution (SR) of 6.670×10−6 RIU.

These pioneering studies collectively underscore the transformative potential of SPR-based PCF sensors, offering unprecedented sensitivity and precision across a spectrum of applications, from cancer cell detection to gas-liquid impurity recognition (11). The integration of advanced materials, innovative designs, and comprehensive numerical analyses has propelled these sensors to the forefront of cutting-edge technologies, promising revolutionary advancements in sensor capabilities and their impact on diverse scientific and technological domains.

The incorporation of gold nanowires in this research paper on SPR-based PCF sensors stands out as a strategic choice with several distinct advantages. Gold, renowned for its unique optical and plasmonic properties, proves highly suitable for enhancing sensor performance (12). The choice of gold nanowires contributes to increased sensitivity and precision due to their strong surface plasmon resonance effects. Unlike other metals, gold exhibits excellent biocompatibility, making it an ideal material for biosensing applications, particularly in the context of cancer cell detection. Additionally, gold's stability and resistance to corrosion ensure the long-term reliability of the sensor. The selection of gold nanowires in this study reflects a thoughtful consideration of material properties, optimizing the sensor's capabilities for precise and reliable refractive index measurements (13). Other metals may lack the combination of optical characteristics, stability, and biocompatibility that gold uniquely offers in the context of SPR-based PCF sensors.Furthermore, we discuss the diverse applications of PCF-based SPR sensing in fields such as biomedicine, environmental monitoring, and industrial analysis, highlighting the potential impact of this technology on various sectors. Additionally, we examine the challenges and future directions in PCF-based SPR sensing, including fabrication complexity, scalability, and cost-effectiveness. By addressing these challenges and exploring emerging technologies, we aim to pave the way for the continued advancement and adoption of PCF-based SPR sensing in research and practical applications.

Overall, this review provides valuable insights into the integration of PCFs with SPR sensing and its potential to revolutionize optical sensing capabilities. Through a thorough examination of recent developments, challenges, and future prospects, we aim to inspire further research and innovation in this exciting field.

Challenges in Traditional Surface Plasmon Resonance (SPR) Sensing

SPR sensing has been a cornerstone technique in the field of label-free detection and analysis for several decades. However, despite its widespread adoption and utility, traditional SPR sensing methods encounter several challenges that limit their effectiveness in certain applications. In this section, we will explore the key challenges associated with traditional SPR sensing and discuss potential strategies to overcome them.One of the primary challenges in traditional SPR sensing is sensitivity limitations, particularly in detecting low concentrations of analytes or small changes in refractive index. Traditional SPR sensors often struggle to achieve high sensitivity, especially in complex sample matrices where background noise can obscure signal detection. This sensitivity limitation poses a significant barrier in applications requiring the detection of trace analytes, such as in biomedical diagnostics or environmental monitoring.Several factors contribute to sensitivity limitations in traditional SPR sensing (15). These include intrinsic noise from the sensor system, non-specific binding of analytes to the sensor surface, and limitations in the optical setup's signal-to-noise ratio. Additionally, traditional SPR sensors may suffer from limited dynamic range, making it challenging to detect analytes across a wide concentration range.

Another challenge in traditional SPR sensing is maintaining stability and reproducibility over extended periods of time. Traditional SPR sensors are sensitive to environmental fluctuations, such as temperature variations, mechanical vibrations, and changes in sample flow rates (16). These fluctuations can lead to drift in baseline signals, affecting the accuracy and reliability of measurements. Furthermore, the reproducibility of SPR sensor responses can be compromised by variability in sensor fabrication, surface functionalization protocols, and experimental conditions.The stability and reproducibility challenges in traditional SPR sensing hinder its application in long-term monitoring studies and high-throughput screening assays. Researchers and practitioners face difficulties in obtaining consistent and reliable data, which can impede the interpretation of results and the comparison of experimental findings across different studies.

Traditional SPR sensors primarily measure changes in the refractive index of the medium near the sensor surface, known as surface sensitivity. While surface sensitivity is advantageous for detecting molecular interactions occurring at the sensor surface, it may not capture changes in bulk refractive index or analyte concentration within the sample volume.This disparity between bulk sensitivity and surface sensitivity can limit the applicability of traditional SPR sensing in certain scenarios, such as monitoring analyte diffusion or concentration gradients in solution. Researchers often require complementary techniques to provide information about bulk properties, leading to increased complexity and cost in experimental setups.Traditional SPR sensing setups can be complex and expensive, requiring specialized instrumentation and expertise for operation and maintenance. The complexity of optical setups, including the alignment of light sources, detectors, and optical components, can pose significant challenges for researchers, especially those with limited experience in optical instrumentation.

Moreover, the cost associated with purchasing and maintaining traditional SPR sensing systems can be prohibitive for many research laboratories and institutions. The high initial investment and ongoing operational expenses, such as consumables and service contracts, may restrict access to SPR sensing technology and limit its widespread adoption across diverse research fields.Multiplexing, the ability to simultaneously measure multiple analytes in a single experiment, is an essential feature in many sensing applications, including biomarker detection, drug screening, and environmental monitoring. However, traditional SPR sensing methods often lack robust multiplexing capabilities, limiting their throughput and efficiency in high-throughput screening assays.Traditional SPR sensors typically rely on a single sensing surface, limiting the number of analytes that can be simultaneously interrogated. While researchers have developed strategies to increase multiplexing capacity, such as microarray-based sensor formats or parallel sensor arrays, these approaches may introduce additional complexity and cost to experimental setups.

Despite these challenges, ongoing research efforts are focused on developing innovative strategies to address the limitations of traditional SPR sensing methods. These strategies leverage advancements in materials science, nanotechnology, signal processing, and instrumentation to improve sensitivity, stability, multiplexing capabilities, and cost-effectiveness of SPR sensing platforms.

Researchers are exploring novel sensor designs and materials to enhance sensitivity and stability in SPR sensing. For example, plasmonic nanostructures, such as metallic nanoparticles or nanostructured thin films, can enhance local electromagnetic fields and improve sensitivity to analyte binding events. Additionally, engineered surface coatings with tailored surface chemistries can minimize non-specific binding and enhance selectivity in SPR sensing applications.Signal enhancement techniques, such as surface amplification or signal amplification strategies, can improve the signal-to-noise ratio and sensitivity of traditional SPR sensors. These techniques involve the use of signal amplifiers, such as enzymes, nanoparticles, or amplification cascades, to amplify the response to analyte binding events, enabling the detection of low concentrations or weak interactions.Integration of SPR sensing with microfluidic platforms offers several advantages, including precise control over sample delivery, reduced sample volumes, and enhanced mass transport to the sensor surface. Microfluidic SPR systems can mitigate stability issues associated with sample flow variations and enable rapid, automated measurements, making them well-suited for high-throughput screening applications (17).

Combining SPR sensing with other sensing modalities, such as fluorescence, surface-enhanced Raman scattering (SERS), or electrochemical sensing, can provide complementary information and improve sensitivity, selectivity, and multiplexing capabilities. Multimodal sensing approaches enable researchers to exploit the strengths of each technique while mitigating their respective limitations, leading to more robust and comprehensive sensing platforms.Advancements in micro- and nanofabrication technologies have enabled the miniaturization and integration of SPR sensing systems onto compact, portable platforms (18). Miniaturized SPR sensors offer several advantages, including reduced sample volumes, lower reagent consumption, and increased portability for on-site or point-of-care applications. Integrated sensor platforms incorporating microfluidics, optics, and electronics further streamline experimental workflows and simplify instrument operation.

Integration of Photonic Crystal Fibers (PCFs) with Surface Plasmon Resonance (SPR) Sensing

Integrating PCFs with SPR sensing enhances sensitivity and signal-to-noise ratio by leveraging the strong light-matter interactions within the PCF core and at the metal-dielectric interface. The subwavelength features of PCFs enable efficient coupling of light to surface plasmons, resulting in improved detection limits and enhanced sensitivity to refractive index changes and analyte binding events.PCF-based SPR sensors offer compact and portable alternatives to traditional SPR setups, enabling miniaturization of sensor platforms for point-of-care diagnostics, environmental monitoring, and on-site detection applications. The small footprint of PCF-based sensors makes them ideal for integration into handheld or wearable devices, facilitating real-time monitoring in diverse settings.Researchers have explored various PCF designs, including solid-core PCFs, hollow-core PCFs, and micro structured fibers, to optimize sensor performance and functionality. Solid-core PCFs with tailored geometries and materials enhance light-matter interactions, while hollow-core PCFs enable reduced sample volumes and enhanced analyte diffusion (19). Micro structured fibers offer flexibility in design and fabrication, allowing for custom sensor configurations tailored to specific applications and analytical requirements.

PCF-based SPR sensors support multiplexing and parallel detection capabilities, enabling simultaneous monitoring of multiple analytes or samples in a single experiment. By integrating multiple PCFs or incorporating microfluidic channels into PCF-based sensor platforms, researchers can achieve high throughput and efficiency in SPR-based assays, making them suitable for high-content screening and large-scale analysis.PCF-based SPR sensing has applications in biomedical diagnostics, environmental monitoring, food safety, and pharmaceutical research. These sensors enable label-free detection of biomolecular interactions, chemical reactions, and environmental pollutants, offering sensitive and selective detection capabilities in complex sample matrices. In biomedical applications, PCF-based SPR sensors facilitate early disease diagnosis, treatment monitoring, and personalized medicine, while in environmental monitoring, they enable real-time detection of contaminants, toxins, and pathogens in air, water, and soil samples.Recent advancements in materials science, nanotechnology, and fabrication techniques have propelled the development of PCF-based SPR sensing platforms (20). Engineers and scientists are continuously innovating new PCF designs, materials, and manufacturing processes to enhance sensor performance, reliability, and scalability. By harnessing the unique properties of PCFs and integrating them with SPR sensing technology, researchers are pushing the boundaries of optical sensing and paving the way for next-generation sensor platforms with unprecedented sensitivity, specificity, and versatility.

Advantages of PCF-based SPR Sensing

PCF-based SPR sensing offers enhanced sensitivity compared to traditional SPR sensors. The unique micro structured design of PCFs enables efficient coupling of light to surface plasmons, resulting in increased signal intensity and improved detection limits. This heightened sensitivity allows for the detection of low-concentration analytes and enables the monitoring of subtle changes in refractive index.PCF-based SPR sensors allow for miniaturization and portability, making them suitable for point-of-care diagnostics and field applications. The compact size of PCF-based sensors enables integration into handheld devices or wearable platforms, facilitating real-time, on-site detection in various environments. This portability enhances accessibility to SPR sensing technology and expands its potential applications beyond laboratory settings.PCF-based SPR sensors support multiplexing capabilities, enabling simultaneous detection of multiple analytes in a single experiment. By integrating multiple PCFs or incorporating microfluidic channels into sensor platforms, researchers can perform parallel analyses, increasing throughput and efficiency. This multiplexing ability enhances the versatility of PCF-based SPR sensing for high-throughput screening and comprehensive analysis.PCF-based SPR sensing enables label-free detection of analytes, eliminating the need for fluorescent or radioactive labels (21). This label-free approach simplifies assay procedures, reduces assay costs, and minimizes the risk of sample contamination. Additionally, label-free detection preserves the native structure and function of biomolecules, providing more accurate and reliable results in biological and biomedical applications.

PCF-based SPR sensing has diverse applications across various fields, including biomedical diagnostics, environmental monitoring, food safety, and pharmaceutical research. These sensors can detect biomolecular interactions, chemical reactions, and environmental contaminants with high sensitivity and specificity. In biomedical applications, PCF-based SPR sensing facilitates disease diagnosis, drug discovery, and personalized medicine, while in environmental monitoring, it enables the detection of pollutants, toxins, and pathogens in complex matrices.PCF-based SPR sensors offer flexibility in sensor design, allowing for customization to meet specific application requirements. Researchers can tailor the geometry, material composition, and surface functionalization of PCFs to optimize sensor performance and functionality. This flexibility enables the development of tailored sensor platforms for different analytes, sample matrices, and experimental conditions, enhancing the versatility and applicability of PCF-based SPR sensing (22).PCF-based SPR sensing offers several advantages over traditional SPR sensors, including enhanced sensitivity, miniaturization, multiplexing capabilities, label-free detection, wide-ranging applications, and flexibility in sensor design. These advantages make PCF-based SPR sensing a valuable tool for various research, clinical, and industrial applications, driving innovation in optical sensing technology and advancing the field of bioanalytic and environmental monitoring.

Applications of PCF-based SPR Sensing

PCF-based SPR sensing finds extensive applications in biomedical diagnostics, including disease detection, biomarker analysis, and drug screening. These sensors enable label-free detection of biomolecular interactions, such as protein-protein binding, antibody-antigen recognition, and DNA hybridization. PCF-based SPR sensing is used for early disease diagnosis, monitoring disease progression, and evaluating treatment efficacy in various medical conditions, including cancer, infectious diseases, autoimmune disorders, and cardiovascular diseases.PCF-based SPR sensing plays a crucial role in pharmaceutical research for drug discovery, development, and quality control. These sensors facilitate the characterization of drug-receptor interactions, ligand-binding kinetics, and drug-target specificity. PCF-based SPR sensing is employed in screening compound libraries, optimizing drug formulations, and assessing drug stability and bioavailability (23). Additionally, these sensors support label-free assays for assessing drug efficacy, toxicity, and pharmacokinetics, accelerating the drug development process and reducing costs.PCF-based SPR sensing offers robust solutions for environmental monitoring, including detection and quantification of pollutants, toxins, and contaminants in air, water, and soil samples. These sensors enable rapid, sensitive, and selective detection of environmental analytes, such as heavy metals, pesticides, organic pollutants, and microbial pathogens. PCF-based SPR sensing is used in environmental surveillance, pollution control, and water quality assessment, providing valuable insights for environmental management and public health protection.PCF-based SPR sensing plays a critical role in ensuring food safety and quality by detecting contaminants, allergens, and adulterants in food products (24). These sensors enable rapid screening of food samples for microbial pathogens, toxins, and chemical residues, ensuring compliance with food safety regulations and standards. PCF-based SPR sensing is used in food processing, distribution, and storage to monitor food quality parameters, such as freshness, nutritional content, and authenticity, contributing to consumer confidence and public health protection.

PCF-based SPR sensing is employed in bioprocess monitoring and biomanufacturing applications for real-time monitoring of cell culture processes, fermentation reactions, and biomolecule production. These sensors enable continuous monitoring of key process parameters, such as cell viability, metabolite concentrations, and product purity, ensuring optimal process control and product quality. PCF-based SPR sensing facilitates process optimization, scale-up, and automation in biopharmaceutical production, leading to improved efficiency, productivity, and cost-effectiveness.PCF-based SPR sensing is emerging as a promising technology for point-of-care diagnostics, enabling rapid and sensitive detection of disease biomarkers, pathogens, and infectious agents at the point of need. These sensors offer portable, user-friendly platforms for on-site testing in clinical settings, remote areas, and resource-limited environments. PCF-based SPR sensing facilitates early disease diagnosis, disease surveillance, and outbreak detection, improving access to healthcare and reducing healthcare disparities globally.PCF-based SPR sensing has diverse applications across various fields, including biomedical diagnostics, pharmaceutical research, environmental monitoring, food safety, bioprocess monitoring, and point-of-care diagnostics. These sensors provide sensitive, selective, and label-free detection capabilities, making them valuable tools for research, clinical diagnostics, and industrial applications. PCF-based SPR sensing contributes to advancements in healthcare, environmental protection, food safety, and biotechnology, driving innovation and addressing global challenges in public health, sustainability, and food security.

Challenges and Future Directions in PCF-based SPR Sensing

One of the primary challenges in PCF-based SPR sensing is optimizing sensor performance to achieve higher sensitivity, selectivity, and reproducibility. Researchers are exploring novel sensor designs, materials, and surface functionalization techniques to enhance the interaction between light and surface plasmons within PCFs. Improvements in sensor fabrication methods and integration of advanced signal processing algorithms are also being pursued to minimize noise and background signals, thereby improving detection limits and assay robustness.Surface effects, such as surface roughness, contamination, and non-specific binding, can significantly impact the performance of PCF-based SPR sensors. Addressing these surface effects requires a thorough understanding of surface chemistry, biomolecular interactions, and surface plasmon resonance phenomena. Strategies for surface passivation, biofouling prevention, and surface regeneration are being developed to minimize unwanted interactions and enhance sensor specificity and stability.Integrating PCF-based SPR sensors with microfluidic systems presents both opportunities and challenges. While microfluidic integration enables sample handling, mixing, and control within a compact and automated platform, it also introduces challenges related to fluid dynamics, flow control, and sensor alignment (25). Researchers are working on developing microfluidic interfaces and fluidic control systems that enable efficient sample delivery, minimize sample consumption, and enhance sensor performance in complex sample matrices.

Standardization and quality control are essential for ensuring the reliability, reproducibility, and comparability of PCF-based SPR sensing data across different laboratories and applications. Establishing standardized protocols, reference materials, and performance metrics for PCF-based SPR sensors is crucial for benchmarking sensor performance, validating assay results, and facilitating technology transfer. Efforts towards standardization and quality control are essential for promoting widespread adoption of PCF-based SPR sensing in research, clinical diagnostics, and industrial applications.Despite significant research progress, the commercialization and scalability of PCF-based SPR sensing technologies remain challenging. Commercialization requires overcoming barriers related to sensor cost, manufacturability, and market acceptance. Scaling up production processes, reducing sensor fabrication costs, and developing user-friendly platforms are essential for transitioning PCF-based SPR sensors from research laboratories to commercial markets. Collaboration between academia, industry, and regulatory agencies is critical for addressing these challenges and accelerating the translation of PCF-based SPR sensing technologies into practical applications.Future directions in PCF-based SPR sensing involve exploring emerging applications and integrating with complementary technologies. Researchers are investigating new application areas, such as single-molecule detection, label-free imaging, and in vivo sensing, to expand the utility of PCF-based SPR sensors in fundamental research and clinical diagnostics (26). Additionally, integrating PCF-based SPR sensing with complementary technologies, such as surface-enhanced Raman spectroscopy, plasmonic nanomaterials, and artificial intelligence, holds promise for enhancing sensor performance, functionality, and versatility in complex analytical tasks. Challenges and future directions in PCF-based SPR sensing include optimizing sensor performance, understanding and mitigating surface effects, integrating with microfluidic systems, standardizing protocols, commercializing technologies, and exploring emerging applications and technologies. Addressing these challenges and pursuing future directions will advance the field of PCF-based SPR sensing, enabling new capabilities, applications, and opportunities for research, diagnostics, and technology innovation.

Enhancing Performance and Emerging Technologies in SPR Sensing

Incorporating nanomaterials, such as metallic nanoparticles, nanorods, and nanoshells, into SPR sensor platforms can enhance performance by amplifying signal intensity, improving sensitivity, and enabling multiplexed detection. These nanomaterials exhibit unique optical properties, including localized surface plasmon resonance (LSPR), which can be exploited to enhance the sensitivity and specificity of SPR sensors. Researchers are exploring novel nanomaterial synthesis methods, surface functionalization strategies, and integration techniques to optimize their performance and compatibility with SPR sensing platforms.Plasmonic engineering techniques, such as Nano structuring, plasmonic antenna design, and metamaterials fabrication, offer opportunities to tailor the optical properties of SPR sensor surfaces and manipulate light-matter interactions at the nanoscale. These approaches enable precise control over plasmon resonance properties, enhancement of near-field effects, and engineering of surface plasmon modes, leading to improved sensor sensitivity, selectivity, and spatial resolution. Plasmonic engineering holds promise for developing next-generation SPR sensor platforms with enhanced performance and functionality for diverse applications (27).

Advanced signal processing techniques, such as machine learning, deep learning, and artificial intelligence, can enhance the data analysis capabilities of SPR sensing platforms, enabling real-time, high-throughput, and automated detection of analytes. Machine learning algorithms can extract relevant information from complex sensor data, identify patterns, and classify analyte interactions with high accuracy and efficiency. Integration of advanced signal processing algorithms with SPR sensing platforms facilitates rapid decision-making, improves assay robustness, and enhances sensor performance in dynamic and complex sample matrices.Microfluidic integration enables precise control over sample delivery, manipulation, and analysis within SPR sensor platforms, enhancing sensitivity, throughput, and automation capabilities. Microfluidic devices provide miniaturized and portable platforms for performing multiplexed assays, kinetic measurements, and sample pre-processing steps, such as sample dilution, mixing, and purification. Integration of microfluidic systems with SPR sensing enables real-time monitoring of biochemical reactions, reduces sample consumption, and improves assay reproducibility and reliability, making it suitable for various applications, including point-of-care diagnostics and high-throughput screening.Label-free imaging techniques, such as surface plasmon resonance microscopy (SPRM) and surface plasmon resonance imaging (SPRI), offer non-invasive and real-time visualization of biomolecular interactions at the nanoscale. These imaging modalities enable spatial mapping of analyte distributions, kinetics, and binding affinities on sensor surfaces, providing valuable insights into molecular interactions and surface dynamics (28). Label-free imaging techniques complement conventional SPR sensing methods by offering enhanced sensitivity, resolution, and multiplexing capabilities, making them valuable tools for fundamental research, drug discovery, and diagnostics.

Hybrid sensing platforms that integrate SPR with complementary sensing modalities, such as fluorescence spectroscopy, electrochemical sensing, and mass spectrometry, offer synergistic advantages for multi-parameter analysis and validation of SPR results. These hybrid platforms combine the strengths of different sensing techniques to overcome limitations, improve detection limits, and enhance analytical performance in complex sample matrices. Integration of SPR with other sensing modalities expands the analytical capabilities of SPR sensor platforms, enabling comprehensive and multi-dimensional characterization of biological, chemical, and environmental samples. Enhancing performance and emerging technologies in SPR sensing involve integrating nanomaterials, leveraging plasmonic engineering, employing advanced signal processing techniques, integrating microfluidic systems, exploring label-free imaging modalities, and developing hybrid sensing platforms. These advancements offer opportunities to improve sensor sensitivity, selectivity, throughput, and functionality for diverse applications in research, diagnostics, and industrial applications. Continued research and innovation in these areas will drive the development of next-generation SPR sensing platforms with enhanced performance and expanded capabilities.

CONCLUSION

In conclusion, the integration of photonic crystal fibers (PCFs) with surface plasmon resonance (SPR) sensing signifies a pivotal advancement in optical sensing methodologies. Throughout this review, we've meticulously examined the profound implications of this fusion, unveiling its transformative potential across various domains.PCFs' innate attributes, characterized by their exceptional refractive index sensitivity, minimal optical loss, and customizable microstructure, lay the foundation for a paradigm shift in SPR sensing. By leveraging these attributes, PCFs empower SPR sensors with unprecedented sensitivity, selectivity, and adaptability, thereby transcending the limitations of traditional sensing platforms.Despite the remarkable progress achieved, significant challenges persist. Optimization of sensor performance, mitigation of surface effects, seamless integration with microfluidic systems, standardization of protocols, and the imperative task of commercialization remain formidable obstacles on the path to widespread adoption.However, the landscape of PCF-based SPR sensing is ripe with opportunities for future exploration and innovation. Pioneering endeavours encompass the exploration of novel applications, advancement of fabrication techniques, refinement of signal processing algorithms, and surmounting scalability hurdles. Through collaborative endeavours and interdisciplinary synergies, the horizon of PCF-based SPR sensing extends far beyond mere technological advancement. The convergence of PCFs with SPR sensing heralds a new era of optical sensing prowess. With a shared commitment to excellence and an unwavering dedication to innovation, we stand poised to unlock the full potential of this symbiotic relationship. Let us embark on this collective journey towards a future illuminated by the transformative capabilities of PCF-based SPR sensing, where boundaries are transcended, and possibilities are limitless.

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