Research Progress on Plastic Optical Fiber (POF) Sensors Based on Surface Plasmon Resonance (SPR)

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Abstract. This study investigates the persistent gap between the high sensitivity of surface plasmon resonance (SPR) technology and its limited portability and affordability in field applications. It aims to provide a comprehensive synthesis of how integrating plastic optical fibers (POFs) with SPR can overcome these constraints and to identify remaining barriers to real-world deployment. A systematic literature review focusing on structural designs (side-polished, double-sided polished, tapered, U-shaped), material systems (gold, silver, graphene oxide, molecularly imprinted polymers), and detection principles (refractive-index, antibody-based, and molecularly imprinted assays). SPR-POF sensors combine label-free, real-time performance with the low cost, flexibility, and disposability of POFs, making them highly attractive for portable and practical sensing platforms. SPR-POF sensors represent a promising platform for point-of-care diagnostics, environmental monitoring, and food-safety assurance. Yet, challenges of long-term stability, reproducibility, and scalable manufacturing must be addressed to enable widespread adoption.

Keywords: Surface Plasmon Resonance; Plastic Optical Fiber; Optical Sensors; Environmental Monitoring; Biomedical Testing.

1. Introduction

Surface plasmon resonance (SPR) sensors are among the most powerful optical sensing platforms developed over the past four decades. Based on the excitation of surface plasmons at a metal–dielectric interface, these devices enable highly sensitive, label-free, and real-time monitoring of biomolecular interactions. Their capacity to achieve rapid, accurate, and non-invasive detection has led to widespread applications in biomedical diagnostics, chemical analysis, environmental monitoring, and food safety.

Traditional SPR systems, however, are typically based on bulky prism couplers or rigid silica optical fibers. While such devices can offer high sensitivity and robust optical performance, their disadvantages—high cost, fragility, and limited suitability for field or point-of-care applications—restrict their broader adoption. As a result, considerable research has been directed toward exploring alternative platforms that retain the advantages of SPR but overcome these practical limitations.

Plastic optical fibers (POFs) have emerged as an attractive option. POFs are low-cost, highly flexible, and mechanically robust compared to conventional silica fibers. They possess a large numerical aperture, enabling efficient light coupling, and are compatible with mass production and disposable device designs. These properties make POFs ideal for integration with portable or wearable systems, addressing the urgent need for low-cost yet high-performance optical sensors. The marriage of SPR with POF technology thus provides a compelling pathway toward next-generation sensing devices.

In recent years, research on SPR-POF sensors has expanded rapidly. Scholars have explored structural designs, such as side-polished or double-sided polished POFs, to enhance plasmon excitation. Advanced material coatings, including gold, silver, graphene oxide, and molecularly imprinted polymers, further improve sensitivity, selectivity, and stability. Meanwhile, detection principles have broadened from general refractive index sensing to particular biochemical assays, reflecting the platform's versatility.

Nevertheless, key challenges remain unresolved. These include improving the detection limit for ultra-low analyte concentrations, ensuring stability and reproducibility in complex real-world samples, and advancing device miniaturization for practical deployment. Moreover, translating laboratory prototypes into commercially viable products faces technical, economic, and regulatory barriers.

This review provides a comprehensive synthesis of the research progress on SPR-POF sensors. The paper first consolidates research status and mainstream technological approaches into a unified analysis. It then highlights representative achievements across refractive index sensing, biomedical testing, and food safety monitoring. Finally, it discusses persisting challenges and outlines prospects, aiming to inspire further innovation in this promising field.

2. Development of SPR-POF Technology

2.1 Evolution from Prism Systems to POF Integration

The development of SPR-POF sensors arose from the need to combine the sensitivity of SPR with the practicality of plastic optical fibers (POFs). Traditional SPR devices relied on prism or glass-fiber-based configurations, which offered excellent sensitivity but were expensive, fragile, and unsuitable for field applications. POFs emerged as an attractive alternative due to their low cost, high flexibility, and ease of processing. These fibers are mechanically robust and allow convenient polishing and coating processes, essential for SPR excitation. Over the past two decades, SPR-POF sensors have transitioned from proof-of-concept laboratory tools to advanced prototypes capable of real-world applications.

2.2 Detection Principles and Sensing Mechanisms

SPR-POF sensors monitor wavelength shifts induced by refractive-index changes at the gold–dielectric interface. Upon binding of an analyte to immobilized receptors, the local refractive index decreases, causing a measurable blue shift in the resonance wavelength. Functionalizing the gold surface with specific receptors enables label-free, highly selective detection. Pasquardini et al. anchored anti-Brucella antibodies and reported a limit of detection of 2.8 bacteria mL^{-1} [4], whereas Passeggio et al. immobilized anti-RSV F-protein antibodies and achieved 0.88 PFU mL^{-1} [5]. These results demonstrate that SPR-POF platforms have evolved into versatile tools for rapid, on-site biomedical and environmental monitoring.

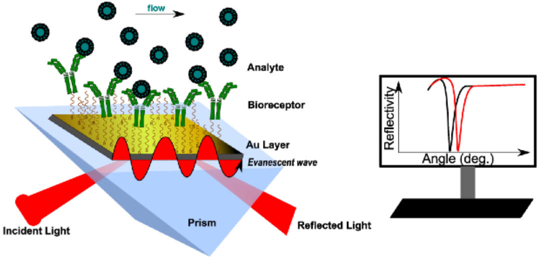

Figure 1. Principle of SPR detection: analyte binding to bioreceptors on the Au layer induces refractive index changes, causing a resonance shift in the reflectivity curve.

3. Structural and Material Innovations

3.1 Structural Designs for Enhanced Plasmon Excitation

Recent works converge on D-shaped, double-sided, polished, tapered, and U-shaped POF geometries to maximize overlap between the guided mode and the surface plasmon. Liu et al. introduced a double-sided polished D-POF that enables light to interact twice with the gold film, raising bulk sensitivity to 4285 nm/RIU [8]. Alberti et al. adopted the same geometry for uranium detection, reporting a 50-nm red-shift increment per MIP layer [1]. Arcadio et al. (2024) demonstrated that a 1-cm-long D-shaped region provides sufficient evanescent field confinement to detect 0.2 pg mL^{-1} cortisol in seawater [3]. Sedeeq et al. further showed that extending the sensing length to 15 mm deepens the SPR dip without spectral broadening, optimizing the figure-of-merit [7]. These studies confirm that precise control of the exposed core length and polishing symmetry is essential for high-resolution, low-noise SPR-POF sensors.

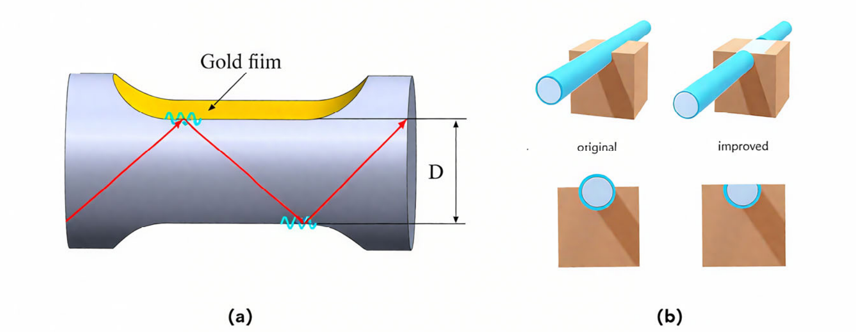

Figure 2. Structural designs of SPR-POF sensors: (a) schematic of a polished POF with a gold film for plasmon excitation; (b) comparison between original and improved embedding configurations for enhanced light–plasmon interaction.

3.2 Plasmonic Materials and Functional Coatings

Gold remains the predominant plasmonic material due to its remarkable chemical stability and biocompatibility, yet alternative coatings such as silver or hybrid films are increasingly explored to improve spectral resolution. For instance, Pasquardini et al. employed a 60 nm Au layer on Ti-primed substrates for Brucella detection, achieving a detection limit of 2.8 cells/mL [4]. Similarly, Alberti et al. coupled Au with an 11-mercaptoundecylphosphonic acid self-assembled monolayer, reporting an affinity constant of 10^7 M^{-1} for uranyl ions[1]. In another approach, Pesavento et al. introduced molecularly imprinted polymers (MIPs) onto Au surfaces, lowering the furfural detection limit to 0.004 mg/L in wine [6]. Sedeeq et al. recently integrated graphene oxide/chitosan nanocomposites with Au films, enhancing amlodipine sensitivity to 2315 nm μM^{-1} [7]. These strategies demonstrate how combining noble-metal films with functional coatings significantly improves the sensitivity, selectivity, and long-term stability of SPR-POF sensors.

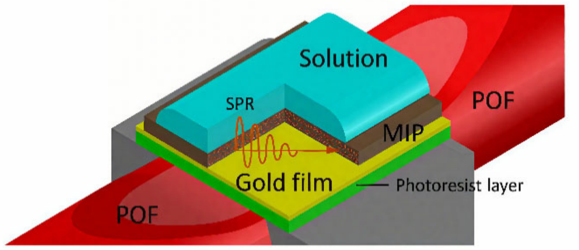

Figure 3. The sensor comprises a plastic optical fiber (POF), a gold film, and a molecularly imprinted polymer (MIP) layer. Light from the POF excites the SPR effect on the gold film, which is then detected. The MIP layer is a functional coating to enhance the sensor's selectivity and sensitivity.

4. Application Results Across Domains

4.1 Refractive Index Detection

Liu et al. presented an enhanced plastic optical fiber surface plasmon resonance sensor with a double-sided polished structure. By symmetrically coating a gold film on both polished surfaces, the sensor achieved an enhanced SPR effect and demonstrated a high sensitivity of 4284.8 nm/RIU for liquid refractive index detection [8]. This device is suitable for applications in fields like the petroleum industry and biochemical sensing, owing to its simple fabrication and low cost. Extending the application to environmental monitoring, Alberti et al. developed a D-shaped POF-SPR sensor to detect uranium ions in water. By incorporating molecularly imprinted polymers (MIPs) as a molecular recognition element, the sensor achieved a selective detection of uranyl ions with a low detection limit in the microgram-per-liter range, providing a rapid, on-site solution for monitoring nuclear contamination risks without the need for time-consuming sample pre-treatment [1].

4.2 Biomedical Diagnostics and Pathogen Detection

Plasmonic optical fiber sensors have significantly advanced the field of biomedical diagnostics, offering a promising solution for rapid and accurate detection of infectious pathogens in diverse settings. Pasquardini et al. developed a proof-of-principle immuno-SPR biosensor based on a D-shaped POF for the on-site detection of the bacterium Brucella abortus. This portable and low-cost device achieved a low limit of detection (LoD) of 2.8 bacteria/mL without requiring a microfluidic system or complex sample treatments, making it highly competitive with other diagnostic systems [4].

Further demonstrating the versatility of this technology, Passeggio et al. introduced a plasmonic biosensor for the ultra-low detection of respiratory syncytial virus (RSV). The sensor was functionalized with an antibody targeting the RSV fusion (F) protein, a highly conserved surface protein that enabled the detection of both RSV subtypes, A and B, in a single test. This device achieved an impressive ultra-low detection limit of approximately 0.88 PFU/mL, with a measurement time of only ten minutes [5]. These studies collectively underscore the potential of SPR-POF sensors as highly effective point-of-care diagnostic tools.

4.3 Food Safety and Quality Monitoring

Surface plasmon resonance-plastic optical fiber sensors have also been effectively applied in food safety, providing a means for rapidly and precisely detecting contaminants and quality indicators. Pesavento et al. developed an SPR-based biosensor using a D-shaped POF combined with a molecularly imprinted polymer (MIP) to specifically detect furfural (2-FAL), a compound that can negatively affect the flavor of wine and is suspected to be toxic and carcinogenic. This portable, low-cost platform was designed for on-site, single-drop measurements, achieving a low detection limit of 0.004 mg/L in a real-world wine matrix [6]. The use of MIPs as biomimetic receptors demonstrated advantages in being straightforward and rapid to develop, and robust under varying conditions, making the sensor a viable alternative to traditional, time-consuming laboratory analyses.

Similarly, in the context of pharmaceutical and food quality assurance, Sedeeq et al. (2025) introduced an ultrasensitive reflective fiber optic sensor for the detection of the drug amlodipine (AML) [7]. This novel sensor was enhanced with a graphene oxide/chitosan (GOCH) nanocomposite layer applied via spin-coating [7]. The device exhibited a remarkable sensitivity of 2315.2 nm/µM and a strong binding affinity of 60.12 μM^{-1}, with its performance validated using real samples and the HPLC method. The sensor also demonstrated excellent stability, showing only a 2.5% decrease in performance over 20 days [7]. These studies highlight the potential of SPR-POF sensors, especially when integrated with advanced nanocomposites or MIPs, to provide robust, highly sensitive, and cost-effective solutions for diverse food and drug safety monitoring tasks.

5. Discussion

5.1 Remaining Technical Limitations

Despite significant progress in designing and applying plastic optical fiber (POF) sensors based on surface plasmon resonance (SPR), several technical constraints remain. First, the intrinsic optical losses of POF, particularly in the visible and near-infrared ranges, limit the sensing distance and restrict device miniaturization. Although perfluorinated POF has reduced attenuation compared with polymethyl methacrylate (PMMA)-based fibers, losses remain substantially higher than those of silica fibers, which can compromise sensitivity and reproducibility in long-range sensing applications[17].

Second, the mechanical flexibility of POF, while advantageous for deployment, introduces challenges in ensuring consistent coupling conditions. Variations in bending or surface roughness can alter plasmon excitation, leading to fluctuations in resonance wavelength and reduced measurement stability [8]. The surface preparation of POF also poses difficulties: achieving uniform thin-film deposition of metals such as Au or Au/ITO multilayers on polymer substrates is less reliable than on silica, due to thermal expansion mismatch and weaker adhesion [11].

Furthermore, environmental influences such as temperature and humidity affect the refractive index of POF and can lead to cross-sensitivity. Thermal expansion of the polymer matrix shifts resonance peaks, reducing accuracy in environments requiring strict stability [18]. Finally, current fabrication strategies often involve manual or semi-automated polishing and coating processes, limiting scalability and increasing sensor variability. These limitations highlight the importance of refined materials and standardized manufacturing methods.

5.2 Future Development Directions

Future research on POF-SPR sensors is expected to focus on material optimization, device integration, and functional diversification. On the materials side, developing novel polymer matrices with lower optical losses and improved thermal stability is essential. Hybrid approaches that combine polymer flexibility with inorganic nanocomposites or protective coatings may also enhance durability [17].

Advances in nanostructured plasmonic films provide another promising pathway. For instance, multilayer structures such as Au/ITO have demonstrated significant sensitivity enhancement compared with single Au coatings, suggesting a viable route toward improving detection limits [11]. Similarly, double-sided polished POF designs have already shown more than 4000 nm/RIU sensitivity, pointing to new structural strategies for enhanced performance [8]. Integrating advanced materials, including graphene or transition metal dichalcogenides, could further strengthen molecular interactions at the sensing surface.

From a system perspective, coupling POF-SPR sensors with microfluidic platforms could support multiplexed, real-time biochemical analysis in portable formats. Such integration may benefit point-of-care diagnostics and environmental monitoring, provided that long-term stability and calibration methods are further developed. Additionally, incorporating POF-SPR sensors into Internet of Things (IoT) frameworks would enable distributed sensing with remote data acquisition and AI-assisted analysis [8].

Finally, scaling up production requires automated polishing and coating methods compatible with polymer substrates. Laser micromachining, roll-to-roll deposition, or chemical surface modification could improve reproducibility and industrial feasibility. Collectively, these strategies point toward the evolution of POF-SPR sensors from laboratory prototypes to robust tools for healthcare, environmental, and industrial applications.

6. Conclusion

This review systematically explored the latest advancements of surface plasmon resonance (SPR)-based plastic optical fiber (POF) sensing technology across various application fields, aiming to provide clear insights and directions for future research. A core finding of this study is the confirmation that combining the SPR phenomenon with the unique advantages of POF enables the development of highly sensitive, selective, and portable biosensors and chemical sensors. This is particularly crucial in scenarios where traditional analytical methods face significant challenges. The research has demonstrated that optimizing sensor structures (such as double-sided polished structures) and surface functionalization strategies (e.g., using MIPs, antibodies, or nanocomposites) can significantly enhance sensor performance. This allows for the ultra-sensitive detection of various targets, including urea, glyphosate, cortisol, *Brucella*, respiratory syncytial virus, furfural, and amlodipine, with detection limits reaching pg/mL or even lower.

The contribution of this study to the field lies in validating the immense potential of SPR-POF sensors as a cost-effective, portable analytical tool suitable for point-of-care testing (POCT). By utilizing technologies like 3D printing, these sensors can achieve customized and rapid prototyping, thereby reducing manufacturing costs and development cycles. Furthermore, these sensors do not require complex sample pre-treatment or signal amplification steps, and they are capable of rapid, in-situ detection directly in complex matrices (such as seawater, wine, and nasopharyngeal swab samples), providing powerful practical tools for fields like environmental protection, food safety, clinical diagnostics, and aquaculture.

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