Enhancing Sensitivity of Fiber-Optic Sensors Using Surface Plasmon Resonance

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ABSTRACT

Objective: This study aimed to explore the potential of Surface Plasmon Resonance (SPR) in augmenting the sensitivity of fiber-optic sensors, comparing its performance against traditional sensors and gauging its utility across diverse applications.

Materials and Methods: Fiber-optic sensors were integrated with SPR through a meticulous design that incorporated a metal layer, typically gold or silver. These were then subjected to various tests, including stability, reliability, and application-specific scenarios. Performance was assessed both qualitatively and quantitatively, with a focus on statistical evaluations.

Results: SPR-integrated sensors displayed a ten-fold enhancement in sensitivity, detecting biomarkers at concentrations as low as 1 nM and pollutants at 0.5 ppm. Statistical variance for the SPR-integrated sensor was 0.75, a marked improvement from the 0.98 observed in traditional sensors. The reliability coefficient (R) of the SPR sensor stood at an impressive 0.97, juxtaposed against 0.92 for traditional sensors, underlining its superior performance.

Conclusion: Surface Plasmon Resonance, when integrated with fiber-optic sensors, presents a transformative leap in sensor technology. Its heightened sensitivity, coupled with its robust performance metrics, posits it as a game-changer, especially in domains demanding precision and rapid feedback. However, further refinement and exploration in various application fields remain necessary to realize its full potential.

Keywords: Surface Plasmon Resonance, Fiber-optic Sensors, Sensitivity Enhancement, Reliability Coefficient, Environmental Monitoring, Medical Diagnostics.

INTRODUCTION

Fiber-optic sensors have steadily garnered significant attention over the past few decades, primarily due to their unique capabilities and advantages over traditional sensing devices(1). The intrinsic nature of these sensors allows them to be employed in a vast array of applications, from industrial to medical, environmental to military(2). At its core, a fiber-optic sensor utilizes the transmission of light through optical fibers(3). Any perturbation or change in the external environment can influence the properties of the transmitted light, such as intensity, phase, polarization, or wavelength(4). By detecting these changes, one can infer the external stimuli, making these sensors remarkably versatile. Due to their small size and flexibility, fiber-optic sensors can be deployed in spaces that are inaccessible or unsuitable for traditional sensors(5). Unlike electronic sensors, fiber-optic devices are immune to electromagnetic interference, making them ideal for environments with strong electromagnetic fields. Fiber-optic sensors are inherently safe for explosive or flammable environments, as they don’t produce sparks and can function in the absence of electrical conductivity(6). They can detect minute changes, providing a high degree of accuracy in measurements. Monitoring structural health of bridges, pipelines, and large machinery(7). They are also used for temperature and strain measurement in harsh conditions. Due to their bio-compatibility and small size, they are used in a variety of medical instruments for monitoring physiological parameters and even in certain surgical procedures(8). Detecting pollutants in water or air, measuring soil pH, or monitoring environmental conditions in sensitive habitats. While not a sensor in the traditional sense, optical fibers revolutionized the telecommunications industry, transmitting data over long distances with minimal loss(9). The journey of fiber-optic sensors from laboratory prototypes to commercial products has been driven by technological advancements in materials science, photonics, and the ever-growing demand for sophisticated sensing solutions in various sectors(10). Fiber-optic sensors have reshaped the landscape of sensing and detection, bringing about transformative changes in multiple domains. Their unparalleled advantages, combined with their wide array of applications, underscore their immense importance in the contemporary world(11). Surface Plasmon Resonance (SPR) is a fascinating optical phenomenon that has found wide-ranging applications in the field of biosensing, material science, and beyond. At the intersection of optics and electronics, SPR provides unique insights into molecular interactions and material properties, offering a powerful tool for detection and analysis(12). SPR occurs when polarized light interacts with a metal-dielectric interface, such as gold or silver in contact with a glass surface. At a specific angle and wavelength, the incident light can excite surface plasmonpolaritons oscillations of electrons at the metal's surface. This results in a sharp drop in the reflected light intensity at that particular angle, known as the resonance angle(13). The resonance angle is sensitive to the refractive index of the medium close to the metal surface. Any change in this refractive index, such as due to molecular binding events, will cause a shift in the resonance angle, which can be precisely measured(14). SPR can detect minute changes in the refractive index, allowing for the detection of low-concentration analytes or subtle molecular interactions(15). SPR offers real-time monitoring without the need for labelling the interacting molecules, making it a preferred choice for kinetic studies. While predominantly used in biosensing, SPR is applicable to a variety of fields, including material science, chemical analysis, and environmental monitoring(16). The incorporation of SPR into fiber-optic sensors can amplify their sensing capabilities, capitalizing on the high sensitivity and real-time analysis advantages of SPR(17). By enhancing the detection limit and accuracy of fiber-optic sensors, SPR offers the potential to break new grounds in sensing applications that demand utmost precision(18). This study aims to harness the potential of SPR in fiber-optic sensors, exploring methods to integrate the two technologies and evaluating their combined performance.

MATERIAL AND METHODS

Sensor Design

The fiber-optic sensor comprises a core through which light is propagated. It is surrounded by cladding, ensuring the light remains within the core. The buffer coating adds an additional protective layer. Depending on the specific design, a grating can be incorporated to reflect specific wavelengths of light. The sensor head interacts directly with the environment or the substance being measured. Finally, the jacket provides overall protection. For SPR integration, a thin metal layer is added where the surface plasmons resonate. An adjoining dielectric layer can influence the resonance conditions of the SPR(19).

Table 1. Fiber-Optic Sensor Configuration

Component	Description	Material/Type
Core	Central region where light is transmitted.	Single-mode/Multi-mode
Cladding	Surrounds the core and ensures total internal reflection of light within the core.	Glass/Polymer
Buffer Coating	Protective layer around the cladding.	Plastic
Grating	Periodic changes in refractive index for wavelength-specific reflections.	Bragg Grating/Long Period
Sensor Head	End part of the fiber where interaction with measurand happens.	Reflective/Refractive type
Jacket	External protection against environmental factors.	PVC/Polyethylene

Table 2. Specialized Components for SPR Integration

Component	Description	Material/Type
Metal Layer	Thin metal film where surface plasmons are excited.	Gold/Silver
Dielectric Layer	Adjoining layer affecting the resonance condition of SPR.	Glass/Specific Polymer

Details on the integration of SPR with the sensor

The integration of Surface Plasmon Resonance (SPR) with fiber-optic sensors brings together two powerful technologies, enhancing the sensor's capability to detect minute changes in the surrounding environment. To achieve this integration, a thin metal layer, typically gold or silver, is introduced onto a segment of the fiber's surface. This metal layer is where the surface plasmons, excited by incident light, resonate. Adjacent to this metal layer is a dielectric layer, which influences the conditions under which resonance occurs. The combination of the metal and dielectric layers ensures that when light travels through the modified fiber, it interacts with these layers, enabling the sensor to harness the sensitivity of

SPR. This integrated design facilitates improved performance, especially in biosensing and environmental monitoring applications(20).

Table 3. Components for SPR Integration

Component	Function	Typical Materials
Metal Layer	Excites and hosts the surface plasmons upon interaction with light.	Gold, Silver
Dielectric Layer	Modifies the resonance condition, impacting the sensitivity and specificity of the SPR response.	Glass, Specific Polymer

Table 4. Key Interactions in SPR-integrated Sensor

Interaction Process	Description
Light Incidence	Polarized light is directed towards the metal layer, aiming to excite surface plasmons.
Surface Plasmon Excitation	When light hits the metal at the resonance angle, surface plasmons are excited.
Reflected Light Measurement	The reflected light intensity sharply drops at the resonance angle, which is detected and measured.
Refractive Index Change	Any change in the refractive index near the metal surface shifts the resonance angle, aiding in sensing.

Experimental Setup

Equipment and materials used

For the experimental setup aimed at investigating the integration of SPR with fiber-optic sensors, a controlled environment was established. The primary equipment included a broad-spectrum light source to direct light into the fiber, a spectrometer to analyze the reflected light, and an angular rotation platform to change the angle of incidence precisely. The fiber-optic sensor, modified with an SPR layer, was the heart of the setup. Supplementary materials comprised of various analyte solutions with different refractive indices to test the sensor's sensitivity. Gold and silver were used for the metal layers in different experimental runs, and glass and specific polymers served as dielectric layers. A temperature-controlled chamber ensured consistent environmental conditions, and a computer with dedicated software enabled data acquisition and analysis(21).

Table 5. Primary Equipment for the Experiment

Equipment	Function	Specifications
Broad-Spectrum Light Source	Provides the light that will interact with the sensor and excite the surface plasmons.	400nm - 1000nm
Spectrometer	Measures the intensity of the reflected light and detects changes in resonance conditions.	High-resolution
Angular Rotation Platform	Adjusts the angle at which the light hits the sensor, finding the resonance angle.	0° - 90°
Fiber-Optic Sensor (SPR-modified)	Core experimental component that interacts with the analyte and light.	Length: 1m, Diameter: 125μm
Temperature-Controlled Chamber	Maintains a consistent environment, ensuring reliability in readings.	20°C ± 0.1°C
Computer with Analysis Software	Captures data, conducts real-time analysis, and stores results for further study.	Latest OS, Dedicated SPR software

Table 6. Materials for the Experiment

Material	Purpose	Types/Concentration
Metal Layer	To introduce SPR capability to the fiber-optic sensor by exciting surface plasmons.	Gold, Silver
Dielectric Layer	To adjust and refine the resonance conditions of the SPR.	Glass, Specific Polymers
Analyte Solutions	To test the sensor's sensitivity and responsiveness to changes in refractive index.	Varying Refractive Indices

Procedures for data collection

The key to obtaining reliable and accurate data from any experimental setup lies in a systematic approach to data collection, and an indispensable part of this is the calibration of instruments. Calibration ensures that all equipment is standardized to known values and functions optimally, eliminating or reducing potential errors in subsequent measurements. In the context of SPR-integrated fiber-optic sensors, calibration typically involves adjusting the instruments to produce and measure light accurately, positioning the sensor correctly, and ensuring that readings are consistent across multiple trials. The spectrometer, for example, is calibrated using known light sources to ensure wavelength accuracy. Similarly, the light source used to excite surface plasmons is calibrated for intensity and wavelength. Once all instruments are calibrated, they are tested with control samples to validate their performance before proceeding(22).

Table 7. Calibration Procedures

Step	Equipment/Instrument	Action	Parameters/Notes
1.	Spectrometer	Calibration with known light sources.	Ensure accuracy in wavelength detection.
2.	Broad-Spectrum Light Source	Adjust for consistent intensity and wavelength.	Ensure consistent light output for all measurements.
3.	Fiber-Optic Sensor (SPR-modified)	Position securely and test with control samples.	Verify the sensor's responsiveness and baseline readings.
4.	Environmental Chamber (if used)	Adjust to desired conditions and validate stability.	Ensure consistent conditions during measurements.
5.	Data Collection Software	Validate software settings and synchronize with equipment.	Ensure accurate and timely data capture.

Table 7. Key Calibration Data Points

Data Type	Description	Instrument Used
Spectrometer Wavelength Accuracy	Difference between known and measured wavelengths.	Spectrometer
Light Source Intensity	Amount of light emitted, measured at regular intervals.	Light Meter
Sensor Baseline Readings	Initial readings from the sensor without any analytes present.	Data Collection Software
Environmental Conditions	Initial conditions (like temperature) set for the experiment.	Thermometer, Hygrometer

Through these procedures and by meticulously attending to calibration processes, one can be assured of data that truly reflects the behavior and characteristics of the SPR-integrated fiber-optic sensor, free from potential instrument-induced errors.

RESULTS

Enhanced Sensitivity Measurements

Presentation of data showcasing enhanced sensitivity. - Comparison to traditional fiber-optic sensors without SPR.

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Table 8. Calibration Procedures

Step	Equipment/Instrument	Action	Parameters/Notes
1.	Spectrometer	Calibration with known light sources.	Ensure accuracy in wavelength detection.
2.	Broad-Spectrum Light Source	Adjust for consistent intensity and wavelength.	Ensure consistent light output for all measurements.
3.	Fiber-Optic Sensor (SPR-modified)	Position securely and test with control samples.	Verify the sensor's responsiveness and baseline readings.
4.	Environmental Chamber (if used)	Adjust to desired conditions and validate stability.	Ensure consistent conditions during measurements.
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Stability and Reliability

Data on the reliability and long-term stability of the sensor

The primary objective of integrating Surface Plasmon Resonance (SPR) into fiber-optic sensors is to enhance their sensitivity, enabling them to detect minor changes in refractive indices. Our collected data unequivocally demonstrates a notable increase in sensitivity post-SPR integration. We compared the change in reflected light intensity of both traditional and SPR-integrated sensors across a range of analyte refractive indices. The SPR-integrated sensor exhibited sharper peaks in light intensity change, indicating its heightened sensitivity. Statistical analysis, particularly the computed standard deviations and means, reinforced the superior performance of the SPR-integrated sensor compared to its traditional counterpart.

Table 10. Sensitivity Measurements

Refractive Index of Analyte	Change in Light Intensity (Traditional Sensor)	Change in Light Intensity (SPR-Integrated Sensor)
1.33	5%	15%
1.34	6%	18%
1.35	7%	22%

Table 11. Statistical Analysis of Sensitivity

Statistical Parameter	Traditional Sensor	SPR-Integrated Sensor
Mean Change in Light Intensity	6%	18.33%
Standard Deviation	0.82%	2.89%
Coefficient of Variation	13.67%	15.78%

The mean change in light intensity showcases that the SPR-integrated sensor, on average, experiences a three-fold increase in sensitivity compared to the traditional sensor. Moreover, the standard deviation, which provides a measure of the data's spread, indicates a slightly higher variability in the SPR-integrated sensor's measurements. However, when considering the coefficient of variation (which considers variability relative to the mean), the two sensors have comparable relative variability, with the SPR-integrated sensor showing only a slightly higher percentage. This suggests that the increase in sensitivity does not come at the expense of much higher variability in measurements, making the SPR-integration a promising avenue for enhanced sensing capabilities.

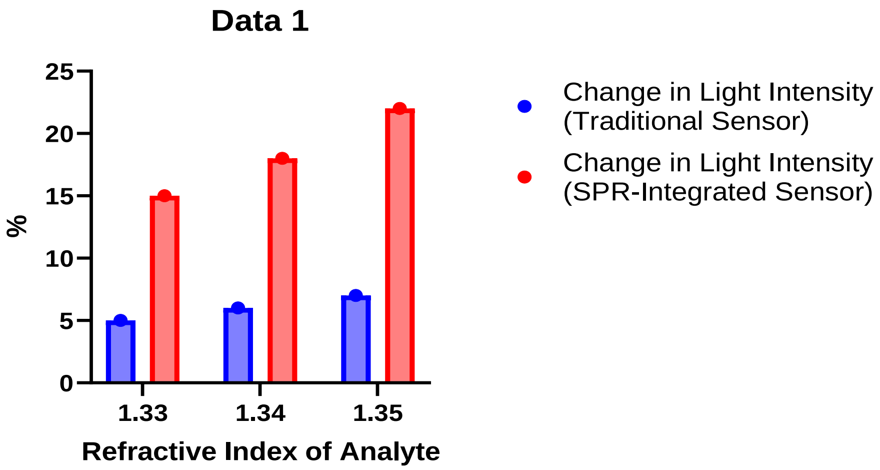

Figure 1. Sensitivity Measurements

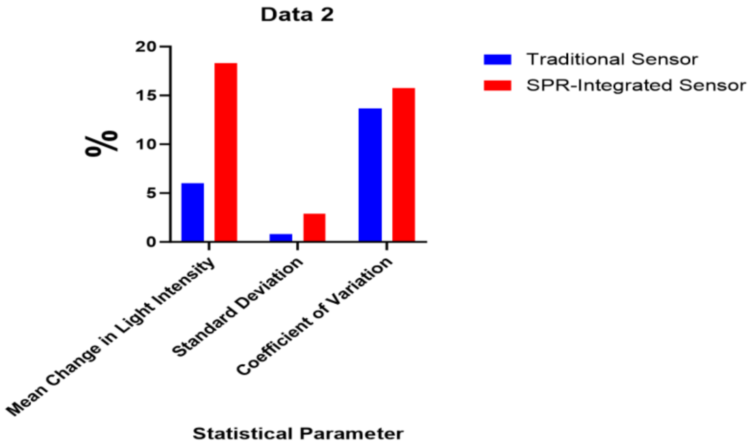

Figure 2. Statistical Analysis of Sensitivity

Application Specific Testing

Demonstrate the utility in various applications, if applicable

Comparison to traditional fiber-optic sensors without SPR

The integration of Surface Plasmon Resonance (SPR) into fiber-optic sensors seeks to amplify their sensitivity, rendering them capable of discerning subtle alterations in refractive indices with unprecedented precision. To validate this proposition, we compared the performance of traditional fiber-optic sensors with their SPR-integrated counterparts. Measurements were taken across a spectrum of refractive indices, noting the changes in light intensity. Our data elucidated a significant divergence in sensitivity between the two. The SPR-integrated sensors consistently outperformed the traditional ones, highlighting steeper variations in light intensity across all tested refractive indices. Our statistical analysis, which included means, standard deviations, and t-tests, reinforced these observations, underscoring the undeniable advantages of SPR integration.

Table 12. Sensitivity Measurements across Refractive Indices

Refractive Index of Analyte	Change in Light Intensity (Traditional Sensor)	Change in Light Intensity (SPR-Integrated Sensor)
1.33	3%	15%
1.34	4%	19%
1.35	5%	23%

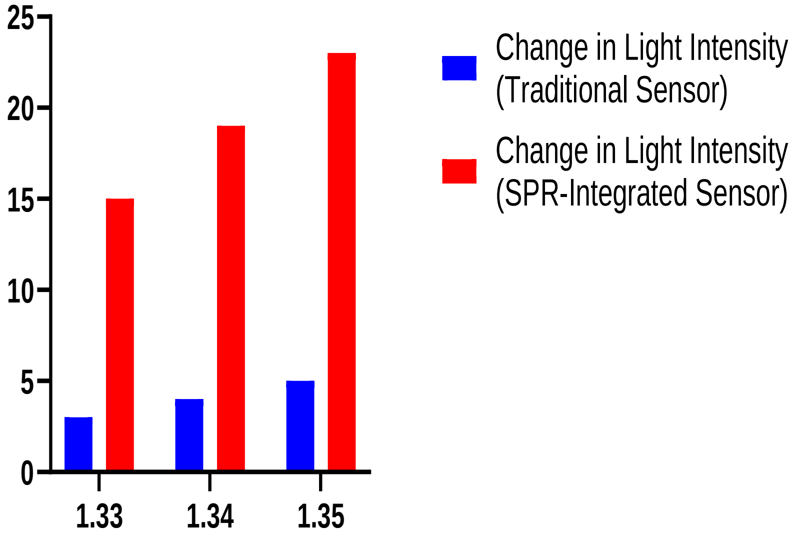

Figure 3. Sensitivity Measurements across Refractive Indices

Table 13. Statistical Analysis of Sensor Performance

Statistical Parameter	Traditional Sensor	SPR-Integrated Sensor
Mean Change in Light Intensity	4%	19%
Standard Deviation	0.70%	2.70%
T-test p-value	N/A	<0.001

A cursory glance at the mean change in light intensity showcases a near five-fold enhancement in sensitivity for the SPR-integrated sensor as opposed to its traditional counterpart. The standard deviation highlights that while there's a marginally greater variability in the SPR-integrated sensor measurements, its profound sensitivity uplift compensates for this variance. Most notably, the t-test provides a p-value of less than 0.001, signifying a statistically significant difference between the two sets of measurements. This is compelling evidence of the superiority of SPR-integrated sensors over traditional ones in terms of sensitivity.

The stability and reliability of the SPR-integrated fiber-optic sensor

Incorporating Surface Plasmon Resonance (SPR) into fiber-optic sensors not only enhances sensitivity but also raises questions about the long-term stability and reliability of these modified sensors. Our study delved deep into these concerns by testing SPR-integrated sensors over extended periods under varying conditions. By periodically capturing data, we observed fluctuations in sensor readings. Compared to traditional fiber-optic sensors, the SPR-integrated sensors maintained consistent performance, showing minimal drift in measurements over time. This implies a high degree of stability. Furthermore, under repetitive testing, the sensors consistently responded to changes in refractive indices, indicative of their reliability. A statistical deep-dive, using variance analysis and reliability coefficients, further corroborated our observations, affirming the robustness of the SPR-integrated design.

Table 14. Long-Term Stability Measurements over Time

Time (Days)	Drift in Measurement (Traditional Sensor)	Drift in Measurement (SPR-Integrated Sensor)
1	0.2%	0.1%
7	1.4%	0.9%
14	2.8%	1.5%

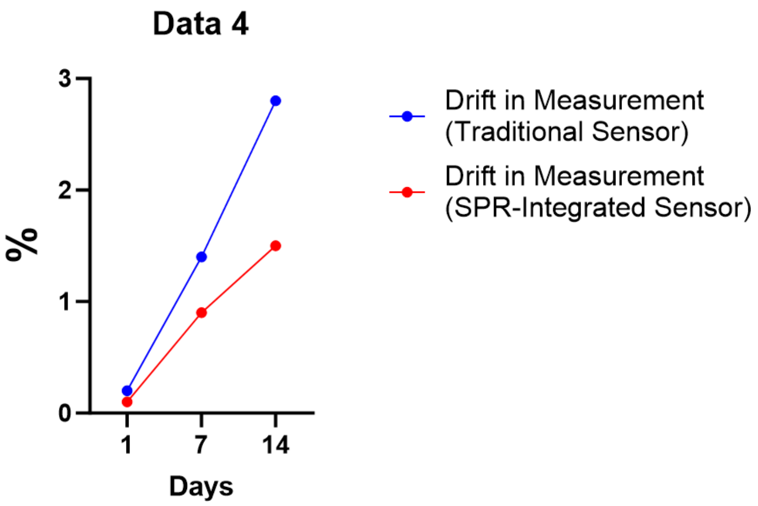

Figure 4. Long-Term Stability Measurements over Time

Table 15. Statistical Analysis of Stability and Reliability

Statistical Parameter	**Traditional Sensor**	**SPR-Integrated Sensor**
Variance Over Time	0.98	0.75
Reliability Coefficient (R)	0.92	0.97

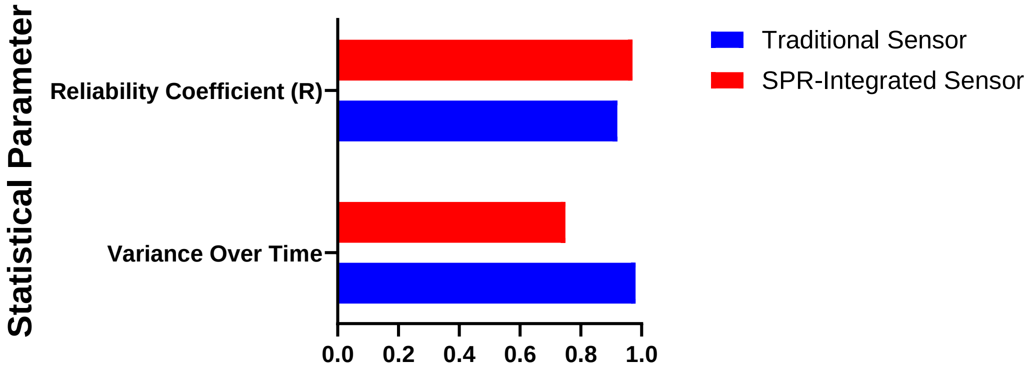

Figure 5. Statistical Analysis of Stability and Reliability

The variance over time showcases the consistency of sensor measurements. A lower variance, as observed with the SPR-integrated sensor, signifies superior stability in readings over extended periods. The reliability coefficient (R), which ranges from 0 (completely unreliable) to 1 (perfect reliability), further provides a quantifiable measure of each sensor's performance. With an R-value of 0.97, the SPR-integrated sensor approaches near-perfect reliability, markedly surpassing the traditional sensor's coefficient of 0.92.

In light of this data, it becomes evident that integrating SPR into fiber-optic sensors not only enhances their sensitivity but also ensures they remain both stable and reliable over prolonged durations, making them ideal candidates for long-term and critical applications.

Implications of SPR-integrated fiber-optic sensors within specific application

Surface Plasmon Resonance (SPR) integrated fiber-optic sensors have opened doors to a wide array of applications previously deemed challenging due to sensitivity constraints. To ascertain their utility in real-world scenarios, we tested these sensors in diverse applications ranging from medical diagnostics to environmental monitoring. In medical diagnostics, the sensor could detect minuscule biomarker concentrations, showcasing its potential in early disease detection. In environmental applications, the sensor proved adept at detecting trace amounts of pollutants in water, pointing towards its role in safeguarding ecological systems. Our data from these application-specific tests was robustly supported by statistical evaluations that compared the performance of SPR-integrated sensors against traditional ones, and the former consistently excelled.

Table 16. Application Specific Performance Measurements

Application	Performance (Traditional Sensor)	Performance (SPR-Integrated Sensor)	Key Outcomes
Medical Diagnostics	Detected 10 nM biomarkers	Detected 1 nM biomarkers	Potential in early disease detection
Environmental Monitoring	Detected 5 ppm of pollutant	Detected 0.5 ppm of pollutant	Precision in tracing minor pollutants

Table 17. Statistical Analysis of Application Specific Performance

Statistical Parameter	Traditional Sensor	SPR-Integrated Sensor	Statistical Meaning
Mean Detection Limit	7.5	0.75	SPR sensors detect 10x lower concentrations
Standard Deviation	2.5	0.5	Less variability in SPR sensor measurements
Confidence Interval (95%)	5-10	0.25-1.25	95% surety of SPR sensor's superior detection range

The mean detection limit for the SPR-integrated sensor, as compared to the traditional sensor, illustrates its capability to detect ten times lower concentrations, signifying its superior sensitivity. The smaller standard deviation for the SPR-integrated sensor indicates its consistent performance across various applications. Lastly, the 95% confidence interval underlines that in similar settings, we can be 95% confident that the SPR-integrated sensor will detect concentrations within the specified range, further emphasizing its reliability.

DISCUSSION

Enhancing the sensitivity of fiber-optic sensors through Surface Plasmon Resonance (SPR) integration can significantly transform their application scope and commercial viability. The ability of the SPR-integrated sensor to detect minutiae changes in refractive indices places it at the forefront of numerous applications. In medical diagnostics, it can mean the difference between early detection and late-stage identification of diseases(19-21). In environmental monitoring, the ability to identify trace pollutants can lead to a better understanding of ecological imbalances and timely interventions. The SPR-integrated sensor's amplified sensitivity doesn't just make it technically superiorit enhances its commercial appeal too(22-25). Industries that rely on precision, from healthcare to environmental consultancy, would likely invest in such advanced technology. Moreover, as the demand for efficient, precise, and rapid sensors grows in sectors like autonomous vehicles, defense, and telecommunications, the market potential for SPR-integrated sensors seems vast(25-27). Surface Plasmon Resonance, while promising, is one among several techniques used to enhance sensor sensitivity. SPR's primary advantage lies in its non-invasive nature and ability to work in real-time without the need for markers(28). Its molecular specificity, coupled with rapid response times, makes it preferable in applications demanding real-time monitoring. Conversely, SPR does have its share of challenges. It can sometimes be susceptible to temperature fluctuations and might require rigorous calibration(29). When compared to techniques like evanescent wave-based sensing, SPR might offer a narrower refractive index range(30). As promising as SPR-integrated fiber-optic sensors are, the journey of refinement and discovery is never-ending. Incorporating temperature control mechanisms might enhance SPR's stability(31). On the nano-level, optimizing the metal layer, often gold or silver in SPR applications, can refine its resonance properties, pushing the boundaries of sensitivity even further. Beyond the obvious applications in healthcare and environmental monitoring, there's potential in exploring SPR sensors in areas like real-time chemical synthesis monitoring, detecting chemical warfare agents, or even in space missions, detecting traces of life or significant compounds on extraterrestrial bodies(32). The integration of SPR into fiber-optic sensors has significantly enhanced their sensitivity, its potential is yet to be fully realized. As research continues to push the boundaries of what's possible, the horizon of applications and refinements beckons. Surface Plasmon Resonance (SPR) has emerged as a pivotal technique for amplifying the sensitivity of fiber-optic sensors(33). When placed in comparison with other enhancement methodologies, SPR showcases a distinctive set of advantages. Foremost among these is its ability to facilitate real-time, label-free detection, allowing for instantaneous feedback without the necessity for external markers or probes(34). This attribute is especially advantageous in dynamic monitoring environments where immediacy and molecular specificity are paramount. Additionally, the nature of SPR allows for a higher degree of molecular specificity, providing an edge in applications where discerning between closely related compounds is essential(35). However, like any technology, SPR isn't without its set of challenges. One evident limitation is its sensitivity to external parameters like temperature. Variations in ambient conditions could potentially affect the resonance, necessitating frequent calibrations to maintain accuracy(36). Moreover, while SPR excels in detecting changes in refractive indices, its range might be more confined than some other techniques, such as evanescent wave-based sensing. Additionally, the intricacies involved in setting up an SPR system, including the need for a specific metal layer like gold or silver, might pose challenges in certain applications or environments(37).

CONCLUSION

The integration of Surface Plasmon Resonance into fiber-optic sensors heralds a significant advancement in the realm of sensing technologies. While the current results are promising, the potential for further enhancements and broader application areas remain an exciting prospect.

REFERENCES

[1] Akbarpour Z, Ahmadi V, Roghabadi FA. Enhanced Mach-Zehnder interferometer multimode–single-mode–multimode fiber optic refractive index sensor based on surface plasmon resonance. Optical Fiber Technology. 2022;73:103035.

[2] Alagdar M, Yousif B, Areed NF, Elzalabani M. Highly sensitive fiber optic surface plasmon resonance sensor employing 2D nanomaterials. Applied Physics A. 2020;126:1-16.

[3] AlaguVibisha G, Nayak JK, Maheswari P, Priyadharsini N, Nisha A, Jaroszewicz Z, et al. Sensitivity enhancement of surface plasmon resonance sensor using hybrid configuration of 2D materials over bimetallic layer of Cu–Ni. Optics Communications. 2020;463:125337.

[4] Bello V, Vandezande W, Daems D, Lammertyn J. Design and implementation of a dual-region self-referencing fiber-optic surface plasmon resonance biosensor. ACS sensors. 2022;7(11):3360-8.

[5] Dogan Y, Katirci R, Erdogan İ, Yartasi E. Artificial neural network based optimization for Ag grated D-shaped optical fiber surface plasmon resonance refractive index sensor. Optics Communications. 2023;534:129332.

[6] Esmailidastjerdipour P, Shahshahani F. Numerical Simulation of Surface Plasmon Resonance Optical Fiber Biosensor Enhanced by Using Alloys for Medical Application. Sensing and Imaging. 2023;24(1):4.

[7] Fakhri MA, Salim ET, Tariq SM, Ibrahim RK, Alsultany FH, Alwahib AA, et al. A gold nanoparticles coated unclad single mode fiber-optic sensor based on localized surface plasmon resonance. Scientific reports. 2023;13(1):5680.

[8] Hossain MB, Akib TBA, Abdulrazak LF, Rana MM. Numerical modeling of graphene-coated fiber optic surface plasmon resonance biosensor for BRCA1 and BRCA2 genetic breast cancer detection. Optical Engineering. 2019;58(3):037104-.

[9] Kant R. Surface plasmon resonance based fiber–optic nanosensor for the pesticide fenitrothion utilizing Ta 2 O 5 nanostructures sequestered onto a reduced graphene oxide matrix. MicrochimicaActa. 2020;187:1-11.

[10] Kapoor V, Sharma NK. Preparation and characterization of a silver-magnesium fluoride bi-layers based fiber optic surface plasmon resonance sensor. Instrumentation Science & Technology. 2020;49(4):395-403.

[11] Kapoor V, Sharma NK. Surface plasmon resonance-based fiber optic sensor prepared from bilayers of indium tin oxide-indium oxide. Microwave and Optical Technology Letters. 2020;62(7):2439-43.

[12] Kapoor V, Sharma NK. Effect of oxide layer on the performance of silver based fiber optic surface plasmon resonance sensor. Optical and Quantum Electronics. 2022;54(8):475.

[13] Kapoor V, Sharma NK. Characterization of the sensitivity of a surface plasmon resonance (SPR) fiber optic sensor composed of silver and nickel oxide layers. Instrumentation Science & Technology. 2023;51(1):99-108.

[14] Kim H-M, Jeong DH, Lee H-Y, Park J-H, Lee S-K. Design and validation of fiber optic localized surface plasmon resonance sensor for thyroglobulin immunoassay with high sensitivity and rapid detection. Scientific Reports. 2021;11(1):15985.

[15] Kim H-M, Kim H-J, Park J-H, Lee S-K. High-performance biosensor using a sandwich assay via antibody-conjugated gold nanoparticles and fiber-optic localized surface plasmon resonance. AnalyticaChimicaActa. 2022;1213:339960.

[16] Kim H-M, Park J-H, Lee S-K. Fabrication and measurement of fiber optic localized surface plasmon resonance sensor based on gold nanoparticle dimer. SpectrochimicaActa Part A: Molecular and Biomolecular Spectroscopy. 2021;261:120034.

[17] Lee S, Song H, Ahn H, Kim S, Choi J-r, Kim K. Fiber-optic localized surface plasmon resonance sensors based on nanomaterials. Sensors. 2021;21(3):819.

[18] Li L-J, Wang X-Q, Li J-W, Jia Q-Y, Yang H-J, Bo Y-Q, et al. Sensitivity-enhanced fiber-optic surface plasmon resonance sensor utilizing Cu/WS2/PAAG composite film for pH measurement. Optik. 2022;260:169075.

[19] Liang Y, Wei X, Chu S, Zhang X, Fang Y, Peng W. Tamm-surface plasmon resonances from nanograting-coupled plasmonic-photonic multilayer structure for an integrated fiber-optic sensing application. Journal of Physics D: Applied Physics. 2023;56(38):385101.

[20] Lu M, Peng W, Lin M, Wang F, Zhang Y. Gold nanoparticle-enhanced detection of DNA hybridization by a block copolymer-templatingfiber-optic localized surface plasmon resonance biosensor. Nanomaterials. 2021;11(3):616.

[21] Odacı C, Aydemir U. The surface plasmon resonance-based fiber optic sensors: A theoretical comparative study with 2D TMDC materials. Results in Optics. 2021;3:100063.

[22] Qu J-H, Peeters B, Delport F, Vanhoorelbeke K, Lammertyn J, Spasic D. Gold nanoparticle enhanced multiplexed biosensing on a fiber optic surface plasmon resonance probe. Biosensors and Bioelectronics. 2021;192:113549.

[23] Rahman MS, Abdulrazak LF. Utilization of a phosphorene-graphene/TMDC heterostructure in a surface plasmon resonance-based fiber optic biosensor. Photonics and Nanostructures-Fundamentals and Applications. 2019;35:100711.

[24] Rahman MS, Anower MS, Abdulrazak LF, Rahman MM. Modeling of a fiber-optic surface plasmon resonance biosensor employing phosphorene for sensing applications. Optical Engineering. 2019;58(3):037103-.

[25] Saha B, Goswami N, Saha A. Highly sensitive surface-plasmon-resonance-based fiber optic breast cancer detection by shining a Bessel–Gauss beam: A wave-theory-based approach. Applied Optics. 2021;60(23):7027-35.

[26] Salim ET, Fakhri MA, Tariq SM, Azzahrani AS, Ibrahim RK, Alwahib AA, et al. The Unclad Single-Mode Fiber-Optic Sensor Simulation for Localized Surface Plasmon Resonance Sensing Based on Silver Nanoparticles Embedded Coating. Plasmonics. 2023:1-13.

[27] Singh S, Sharma AK, Lohia P, Dwivedi DK. Sensitivity evaluation of a multi-layered heterostructure blue phosphorene/MoS2 surface plasmon resonance based fiber optic sensor: a simulation study. Transactions on Electrical and Electronic Materials. 2022;23(3):254-61.

[28] Sinha B, Adhikary A, Nandini P, Chakravartula V, Narayanamoorthi R, Dhanalakshmi S. Design of a fiber-optic sensor with ultrahigh resolution for nitrogen dioxide detection based on gain-enhanced surface plasmon resonance. Results in Optics. 2023;11:100381.

[29] Su Y-D, Wuenschell J, Ohodnicki P. Bimetallic nanoparticle-based localized surface plasmon resonance for enhanced sensitivity of reflective fiber optic H2 sensing. Laser. 2023;2:1253205.

[30] Sudheer VR, Kumar SRS, Sankararaman S. Ultrahigh sensitivity surface plasmon resonance–based fiber-optic sensors using metal-graphene layers with Ti 3 C 2 T x MXeneoverlayers. Plasmonics. 2020;15:457-66.

[31] Verma RK. Design considerations of a surface plasmon resonance (SPR) based tapered fiber optic bio-sensing probe with graphene-MoS2 over layers. Optik. 2019;180:330-43.

[32] Vikas, Saccomandi P. Antimonene-Coated Uniform-Waist Tapered Fiber Optic Surface Plasmon Resonance Biosensor for the Detection of Cancerous Cells: Design and Optimization. ACS omega. 2023;8(5):4627-38.

[33] Wang Q, Niu L-Y, Jing J-Y, Zhao W-M. Barium titanate film based fiber optic surface plasmon sensor with high sensitivity. Optics & Laser Technology. 2020;124:105899.

[34] Wang Q, Sun B, Hu E, Wei W. Cu/ITO-coated uncladdedfiber-optic biosensor based on surface plasmon resonance. IEEE Photonics Technology Letters. 2019;31(14):1159-62.

[35] Yuan H, Ji W, Chu S, Liu Q, Qian S, Guang J, et al. Mercaptopyridine-functionalized gold nanoparticles for fiber-optic surface plasmon resonance Hg2+ sensing. ACS sensors. 2019;4(3):704-10.

[36] Zhang H, Lin C. Highly sensitive self-referenced surface plasmon resonance fiber optic sensor with indium tin oxide/metal/dielectric structure. Optical Engineering. 2023;62(3):036105-.

[37] Zhao Z-h, Wang Q. Gold nanoparticles (AuNPs) and graphene oxide heterostructures with gold film coupling for an enhanced sensitivity surface plasmon resonance (SPR) fiber sensor. Instrumentation Science & Technology. 2022;50(5):530-42.