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Fiber-Optic SPR Sensor Based on MMF-SMF-MMF Structure for Detection of Compositional Variations in Diesel Fuel

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Abstract

The article presents a fiber-optic surface plasmon resonance sensor based on a multimode–single-mode–multimode fiber structure for detecting compositional variations and differentiating diesel fuel grades. The sensor design, modelling approach, and experimental implementation are described. To enhance the sensitivity and contrast of the resonant response, the central 15–17 mm section of the single-mode fiber was coated with a multilayer Al/Al_2O_3 structure. Numerical modelling was performed using the Kretschmann configuration and the transfer matrix method. Experimental measurements were conducted using 50 diesel fuel samples with different physicochemical characteristics. A monotonic dependence of the resonance wavelength on the refractive index was demonstrated, enabling differentiation between standard and arctic diesel fuel. The developed sensor exhibited an average sensitivity of 13300 nm per refractive index unit. The potential and limitations of refractive-index-based sensing for diesel fuel quality control are also discussed.

Keywords: Fiber-optic sensor; Surface plasmon resonance; SPR; Diesel fuel adulteration; Refractive index measurement

1. INTRODUCTION

The global vehicle fleet continues to expand, surpassing 1.644 billion units in 2025, which has led to an increase in fuel consumption worldwide [1]. Maintaining fuel integrity presents a significant challenge, as adulteration with less expensive or lower-grade additives can detrimentally affect engine performance, induce knocking, accelerate corrosion, and elevate maintenance costs, thereby diminishing both safety and efficiency of the engine. Despite regulatory measures, fuel adulteration remains a substantial concern, leading to engine inefficiency, corrosion, and safety hazards for users. Detecting fuel adulteration presents both technical and economic challenges, necessitating the development of innovative solutions.

Fiber-optic sensors have emerged as promising tools for liquid analysis because of their high sensitivity, portability, resistance to electromagnetic interference, and low-maintenance requirements. Among these, sensors based on the principle of surface plasmon resonance (SPR) are particularly notable. SPR-based sensors function by detecting shifts in the resonant wavelength caused by changes in the refractive index of the surrounding medium, which is highly sensitive to alterations in the chemical composition [2–4]. These sensors are renowned for their exceptional sensitivity, selectivity, and ability to analyse samples with minimal or no pre-treatment [5,6].

Various analytical approaches have been investigated for the characterization and detection of fuel adulteration, including physicochemical, chromatographic, and spectroscopic methods [7]. Portable solutions based on absorbance spectroscopy and microfabricated gas chromatography have demonstrated the potential for rapid detection and classification of adulterated diesel fuels [8]. More recently, attenuated total reflectance – Fourier transform infrared spectroscopy combined with chemometric methods has been applied for the profiling and identification of adulterated petroleum products, while electronic-nose systems have been used to classify gasoline, diesel, and kerosene mixtures at different concentrations [9,10]. These approaches demonstrate the potential of optical and sensor-based techniques for rapid fuel quality assessment, although the complexity

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of the analytical equipment and data processing can limit their application in compact and field-deployable systems.

Fiber-optic sensors provide an attractive alternative for fuel quality monitoring due to their compactness, remote sensing capability, and sensitivity to changes in the refractive index of the surrounding medium. Long-period fiber gratings have been investigated for hydrocarbon detection and fuel quality control [11], while fiber-optic SPR sensors have been demonstrated for detecting and quantifying kerosene adulteration in diesel and petrol based on changes in refractive index [12]. Other optical fiber approaches, including higher-order Bessel-Gauss beam propagation and tilted fiber Bragg gratings, have also demonstrated sensitivity to changes in fuel composition [13,14]. These studies confirm the potential of fiber-optic technologies for fuel quality analysis and provide a basis for further development of compact SPR-based sensors for the differentiation of diesel fuel samples.

In this study, the term "diesel fuel adulteration" refers to deviations in the composition and physicochemical properties of diesel fuel from those characteristics of the declared fuel grade. In particular, the present work focuses on the identification of diesel fuel type and climatic grade, which depend on fuel composition and affect its refractive index and density. The proposed sensor is therefore intended primarily for detecting compositional variations and differentiating fuel grades based on their optical properties. The detection of specific forms of contamination, such as water and mechanical impurities, is considered as a separate direction for further development of the proposed sensing approach.

This study presents and validates a novel fiber-optic SPR sensor employing a multimode–single-mode–multimode (MMF-SMF-MMF) fiber configuration. The design incorporates optimized multilayer coatings to enhance the sensitivity and shift the resonant response into the visible spectral range. By integrating theoretical modelling with experimental design, we aim to develop a compact, highly sensitive sensor for the rapid and reliable detection of compositional variations in diesel fuel and differentiation of fuel grades. Our approach combines mathematical modelling using the Kretschmann configuration and matrix method with the practical fabrication and testing of the sensor. The sensor can be used to detect compositional variations in diesel fuel and distinguish fuel grades, contributing to the development of practical next-generation tools for rapid fuel quality control.

The significance of this study lies in its potential to provide a framework for portable analytical systems in the energy and transport sectors, offering a more efficient and accessible method for detecting fuel quality variations. This research not only contributes to the advancement of SPR sensor technology but also addresses critical needs in fuel quality assurance.

2. MATERIALS AND METHODS

2.1. Modelling and sensor design

The optical characteristics of the proposed MMF-SMF-MMF fiber-optic sensor were analysed through numerical modelling. Simulations were performed in Mathcad using the Kretschmann configuration and the transfer matrix method [15,16]. The model allowed optimization of the multilayer coating thickness to achieve maximum SPR sensitivity and to shift the resonance into the visible spectral region, facilitating clear spectral differentiation of diesel fuels.

A schematic structure of the designed sensor is shown in Figure 1, illustrating the central SMF segment (core di-

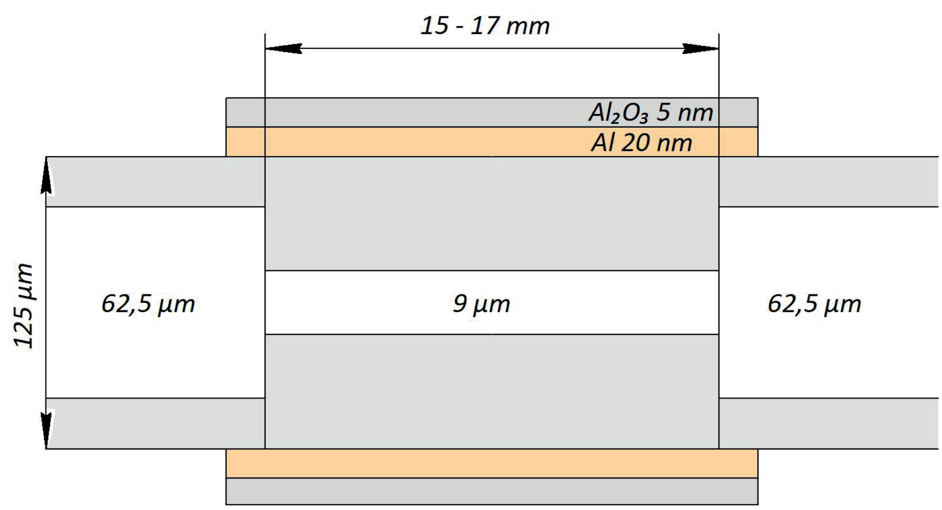

Fig. 1. Structural schematic of the MMF-SMF-MMF fiber-optic sensor. The central SMF segment with a 9 µm core and 125 µm cladding is coated with a 20 nm aluminium layer and 5 nm aluminium oxide dielectric layer over a 15–17 mm length and spliced between two MMFs with 62.5 µm cores and 125 µm claddings.

ameter = 9 µm, cladding = 125 µm) coated with a 20 nm aluminium layer and 5 nm aluminium oxide dielectric layer over a 15–17 mm length, spliced between two MMF sections (core = 62.5 µm, cladding = 125 µm).

The length of the central SMF section was selected as an experimental compromise between providing a sufficiently long interaction region for SPR excitation and maintaining adequate transmitted optical power and fabrication reproducibility. An initial 10 mm sensing region was investigated in preliminary experiments [15], while a length of approximately 15–17 mm was used for the final sensing elements.

2.2. Fabrication of the sensing element

The sensing element was fabricated by sequential splicing of MMF and SMF sections. The SMF segment was cleaved to a length of 15–17 mm using a Fujikura CT-30 fiber cleaver. The second MMF section was spliced using a Fujikura FSM-100P fusion splicer to ensure low-loss optical coupling.

A multilayer coating was then deposited on the exposed SMF region. The structure consisted of a 2 nm chromium adhesion layer, a 20 nm aluminium film, and a 5 nm Al_2O_3 dielectric overlayer, deposited by thermal evaporation in a Kurt J. Lesker PVD 75 system under high-vacuum conditions.

2.3. Experimental setup

The experimental configuration is shown in Figure 2. A halogen lamp (AlfaBright) served as a broadband light source, coupled to the input end of the sensing element. The transmitted spectrum was collected by a spectrometer (Avesta) connected to the output fiber. Spectral data were acquired and analysed using a computer interface. The sensing element was tested in contact with distilled water, ethanol, and diesel fuel samples. The studied set of 50 diesel fuel samples was transferred with supplier certification, which included density at 15 °C as a key parameter. Refractive index measurements were performed using an IRF-454 refractometer, with the polished surface and cover plate carefully cleaned with alcohol after each measurement to ensure accuracy.

2.4. Data processing

Spectral data were processed to determine the characteristic SPR wavelength, defined as the point where the second derivative of the transmission spectrum equalled zero. This method provided improved accuracy and reproducibility compared to locating the first-derivative zero, which is more sensitive to noise.

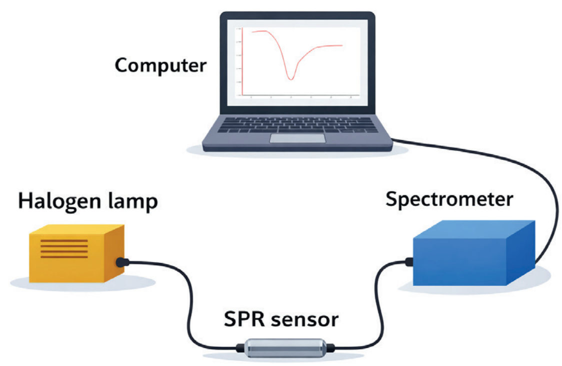

Fig. 2. Experimental setup for spectral measurements of the SPR-based fiber-optic sensor. The configuration includes a halogen lamp (light source), the MMF-SMF-MMF sensing element, a spectrometer, and a computer for data acquisition and analysis.

To enhance spectral contrast and improve the differentiation of optically similar media, a reference medium with a refractive index higher than that of air can be employed. For instance, using distilled water ($n \approx 1.333$) as a reference instead of air significantly alters the reflectance and transmittance profiles, allowing for clearer discrimination between pure water and glucose solutions (Fig. 3). This approach highlights subtle variations in composition that might otherwise be indistinguishable. In this study, to achieve even greater spectral separation and more reliable identification of fuel samples, a reference medium (aqueous 55% glucose solution) with a refractive index of $n = 1.426$ was utilized.

3. RESULTS AND DISCUSSION

3.1. Theoretical modelling and sensor design

Numerical simulations of the MMF-SMF-MMF structure with Al/Al_2O_3 coatings demonstrated a stable and well-defined SPR response within the refractive index range relevant to diesel fuels (~1.4 RIU). As shown in Fig. 4, the modelled spectra reveal that the dielectric overlayer enhances the resonance contrast while shifting the plasmonic dip toward the visible region. This shift is advantageous for the experimental setup and improves the signal-to-noise ratio. These features confirm that the chosen multilayer configuration should support monotonic and measurable wavelength shifts with increasing refractive index.

3.2. Correlation between refractive index, density, and fuel type

Measurements of 50 diesel samples showed that refractive index and density, while not perfectly linearly related, follow a clear and repeatable trend. Denser standard cli-

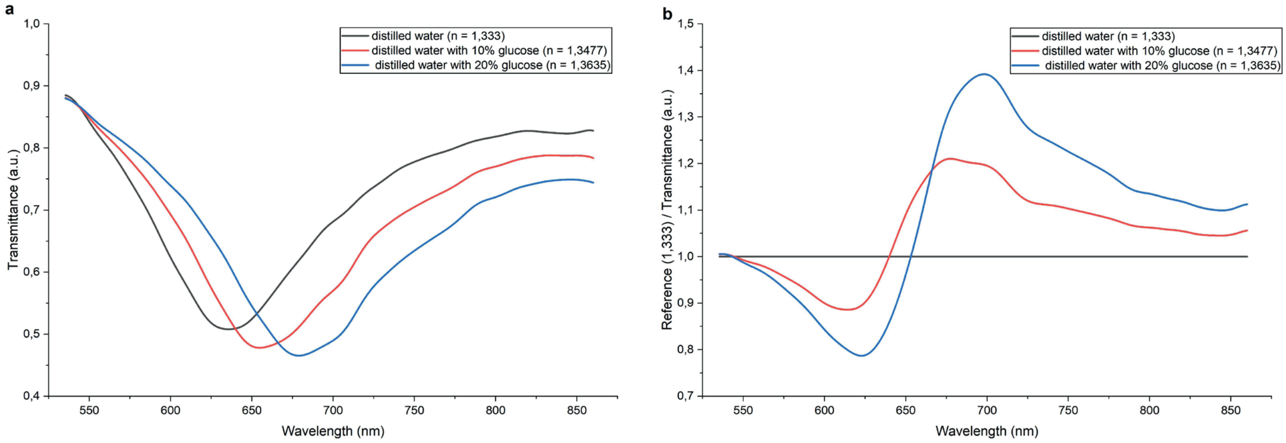

Fig. 3. Spectral transmittance of distilled water and glucose solutions at different concentrations: (a) measured with air as a reference, showing minimal spectral contrast; (b) measured with distilled water (n = 1.333) as a reference, revealing enhanced optical differentiation between the samples. The use of a reference medium with a refractive index close to that of the samples facilitates the identification of SPR dip and significantly improves the visibility of subtle compositional differences. This principle is extended in the present study by employing a reference medium with a refractive index of n = 1.426 to achieve even greater discrimination between standard and arctic diesel fuels.

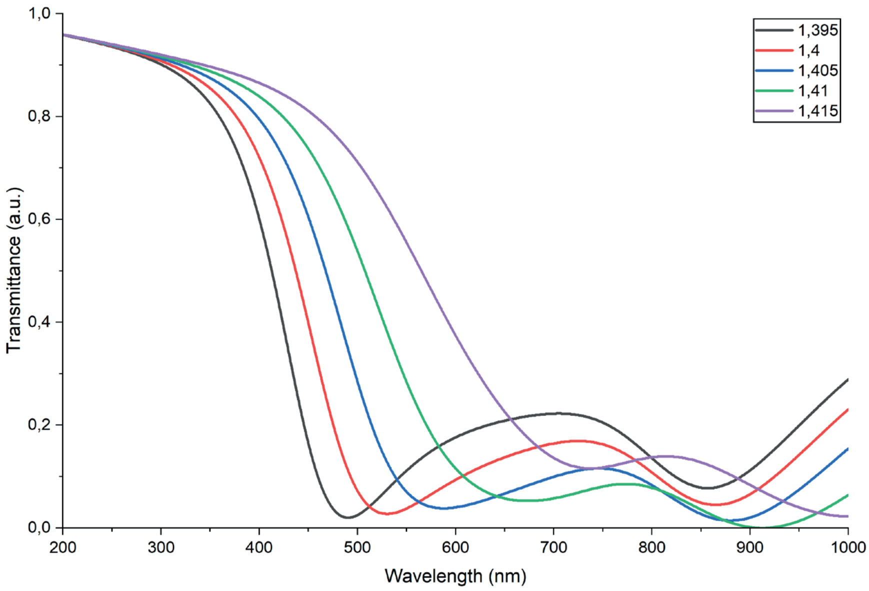

Fig. 4. Simulated SPR transmittance spectra of the MMF-SMF-MMF sensor with Al/Al_2O_3 coatings for different refractive indices. The dielectric overlayer enhances resonance contrast and shifts the plasmonic dip into the visible region, enabling compatibility with the experimental setup.

mate diesel (> 826 kg/m^3) exhibited higher refractive indices (RI), whereas winter and arctic grades (< 822 kg/m^3) clustered at the lower end. It should be noted that arctic diesel exhibits a RI typically in the range of 1.45–1.451, while standard diesel shows higher values, usually 1.456–1.458. This distribution is illustrated in Fig. 5.

Notably, the spread within each fuel category remained narrow, which suggests that combined use of RI and density can serve as a practical classifier for distinguishing fuel grades and identifying adulteration. The overlap observed between borderline summer–winter samples match previously reported behaviour for commercial diesel blends, reinforcing the relevance of these parameters in field diagnostics.

3.3. Spectral characteristics and determination of resonant wavelengths

Representative experimental SPR transmission spectra for several diesel samples, referenced to the 1.426 RIU calibration solution, are presented in Fig. 6. The characteristic resonance wavelengths were determined using the zero

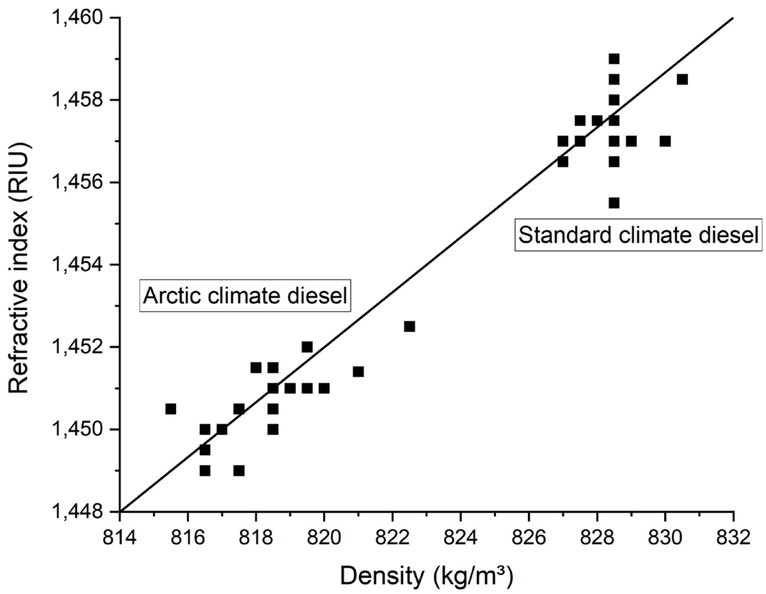

Fig. 5. Correlation between refractive index and density measured for 50 diesel fuel samples. Standard and arctic climate grades form distinct clusters, illustrating the diagnostic potential of combining both parameters for fuel classification.

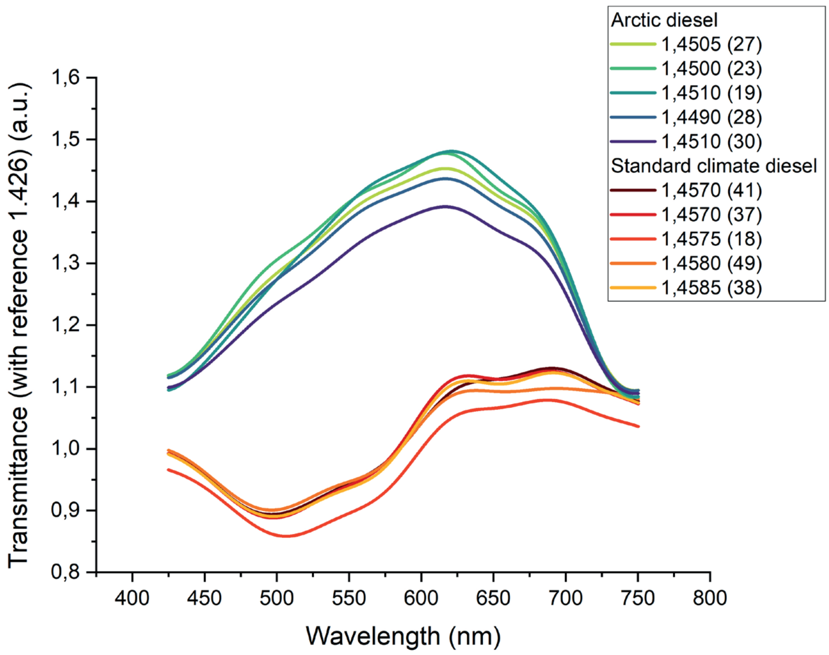

Fig. 6. Experimental dependence of the resonance wavelength on the external refractive index measured for the fabricated MMF-SMF-MMF sensors. The observed trend demonstrates the device response across the RI range relevant to diesel fuels.

of the second derivative, which yielded stable and reproducible values even for shallow minima. In all samples, higher refractive index corresponded to a redshift of the resonance, producing clean spectral separation between fuel categories.

Standard diesel consistently exhibited resonances above 550 nm, while arctic diesel shifted toward shorter wavelengths near 520 nm. This gradual redshift with increasing refractive index is reflected directly in the experimental wavelength–RI dependence shown in Fig. 7. The data in Fig. 7 demonstrate a monotonic increase in resonance wavelength across the measured refractive index interval. Since each diesel fuel sample was measured once, the repeatability of the measurements could not be statistically evaluated. The resonance wavelength was determined from the recorded SPR spectra, and the sensitivity was estimated from the experimentally obtained resonance wavelength shifts. The consistency between

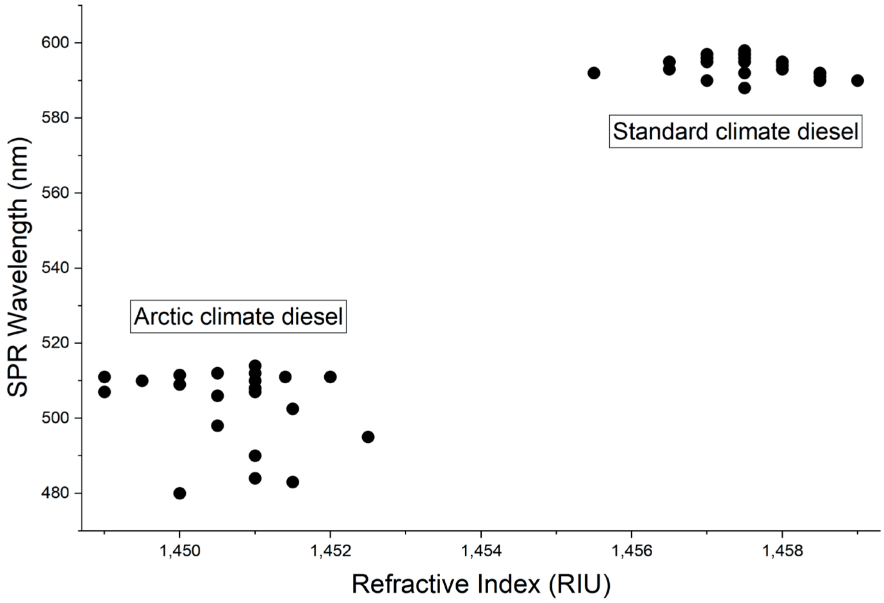

Fig. 7. Experimental SPR transmission spectra for representative diesel samples, with characteristic wavelengths extracted using the zero of the second derivative. The spectral redshift from arctic to standard diesel matches the experimental RI–wavelength trend shown in Fig. 6.

the individual spectra in Fig. 7 and the consolidated trend in Fig. 6 confirms that the fabricated MMF-SMF-MMF structure maintains stable plasmonic coupling and predictable spectral behaviour under real measurement conditions.

3.4. Sensor sensitivity

The sensitivity of the MMF-SMF-MMF sensor was evaluated as the resonance wavelength shift normalized by the corresponding refractive index change:

$$S_{\mathrm{Al+Al_2O_3}} = \frac{\Delta\lambda}{\Delta RI} = \frac{594.348 - 503.883}{1.4575 - 1.4507} \cong 13300 \text{ nm/RIU}. \quad (1)$$

The Al/Al_2O_3-coated MMF-SMF-MMF configuration demonstrated a sensitivity of approximately 13300 nm/RIU (refractive index unit) over the investigated refractive index range. The reported value should be considered in conjunction with the instrumental wavelength accuracy and the single-measurement procedure used for each sample. A systematic evaluation of measurement repeatability and sensitivity uncertainty based on repeated measurements is beyond the scope of the present dataset.

The high sensitivity can be attributed to the optimized field confinement at the metal–dielectric interface and the enhanced modal interaction enabled by the MMF-SMF-MMF geometry. Similarly, to the strong experimental agreement observed in Fig. 6 and Fig. 7, these results validate the design strategy and demonstrate the sensor's suitability for detecting small refractive index variations associated with diesel fuel adulteration.

3.5. Discussion

The experimental results confirm that the MMF-SMF-MMF sensor with an Al/Al_2O_3 coating is effective for differentiating diesel fuel samples with different physicochemical characteristics, demonstrating a strong and monotonic resonance wavelength shift with increasing refractive index and achieving a high average sensitivity of 13300 nm/RIU. Its performance, which stems from the optimized plasmonic field confinement and the sensor's geometry, successfully enabled the classification of diesel fuels, as the measured resonance wavelengths provided clear spectral separation between standard and arctic grades that directly correlated with the established refractive index-density relationship. The narrow data spread within each fuel category and the minimal scatter in the sensor's response confirm its robustness and reproducibility, validating the design as a reliable platform for resolving the subtle refractive index variations associated with differences in diesel fuel composition.

A comparison of the proposed sensor with recently reported fiber-optic sensors is presented in Table 1. The proposed MMF-SMF-MMF SPR sensor demonstrates a sensitivity of approximately 13300 nm/RIU, exceeding the sensitivity values reported for the compared fiber-optic sensors. Although the reported sensors operate with different sensing principles and target media, the comparison highlights the high wavelength sensitivity of the proposed approach for diesel fuel analysis.

In the context of this study, diesel fuel adulteration is considered in terms of deviations in composition and

Table 1. Comparison of sensitivity of a few recently reported fiber optic sensors.

Sensor / sensing principle	Target	Sensitivity	Dynamic range	Ref.
Etched fiber Bragg grating (eFBG) sensor with TiO_2	Petrol Diesel	54.98 nm/RIU 32.25 nm/RIU	–	[17]
Localized surface plasmon resonance (LSPR) sensor based on the U-bent plastic optical fibre (U-POF)	Ethanol solution	700.3 nm/RIU	1.330–1.3657	[18]
Long-period gratings (LPG) fiber sensor	Petrol + kerosene	3071.6 nm/RIU	–	[19]
SMF-MMF-SMF multimode interference (MMI) sensor	E50 ethanol–gasoline and G87 gasoline	390.88 nm/RIU	1.373–1.420	[20]
MMF-SMF-MMF SPR sensor with Al/Al_2O_3	Diesel fuel	13300 nm/RIU	Measured RI range	This work

physicochemical properties from those characteristic of the declared fuel grade. Therefore, the obtained results demonstrate the capability of the proposed sensor to detect compositional variations and differentiate diesel fuel grades based on their optical properties. However, a key limitation of this approach is its fundamental operating principle; as a refractive index sensor, it cannot identify the specific chemical composition of an adulterant, meaning it can reliably flag anomalous samples but cannot distinguish between different contaminants, such as kerosene versus gasoline, without supplemental analytical techniques. The detection and identification of specific forms of contamination, such as water and mechanical impurities, require additional controlled experiments and are considered as a direction for further development of the proposed sensing approach.

4. CONCLUSION

The developed MMF-SMF-MMF fiber-optic SPR sensor demonstrates a high average sensitivity of 13300 nm/RIU and reliable performance for detecting compositional variations in diesel fuel and differentiating fuel grades. Both numerical modelling and experimental results confirm a stable, monotonic resonance wavelength shift in response to refractive index variations characteristic of different diesel grades. The clear spectral separation observed between standard and arctic fuels, together with the low measurement scatter, indicates good reproducibility and robustness of the proposed sensing approach under practical conditions.

The incorporation of Al/Al_2O_3 multilayer coatings significantly enhances the sensor performance by improving plasmonic field confinement and shifting the resonance into the visible spectral range. This design strategy not only increases sensitivity but also supports the development of compact and portable analytical systems suitable for fuel quality control in the energy and transport sectors. Overall, the proposed sensor architecture provides a promising framework for rapid, cost-effective, and field-deployable detection of compositional variations in diesel fuel and differentiation of fuel grades.

A key limitation of the proposed approach is that, as a refractive index sensor, it cannot identify the specific chemical composition of an adulterant. Therefore, while the sensor can detect deviations in the physicochemical properties of diesel fuel and differentiate samples with different compositions, identification and quantification of specific contaminants or adulterants require additional analytical techniques and controlled experiments. In particular, the detection of water and mechanical impurities represents a direction for further development of the proposed sensing approach.

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УДК 681.7.068

Волоконно-оптический ППР-датчик на основе структуры MMF-SMF-MMF волокна для обнаружения примесей в дизельном топливе

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Аннотация. В настоящей статье представлен волоконно-оптический датчик поверхностного плазмонного резонанса на основе структуры многомодовое–одномодовое–многомодовое волокно, предназначенный для обнаружения изменений состава и дифференциации марок дизельного топлива. Рассмотрены конструкция чувствительного элемента, результаты численного моделирования и экспериментального исследования разработанного датчика. Для повышения чувствительности и контрастности резонансного отклика центральный участок одномодового волокна длиной 15–17 мм покрыт многослойной структурой Al/Al_2O_3. Численное моделирование выполнено с использованием конфигурации Кречманна и матричного метода. Экспериментальные исследования проведены для 50 образцов дизельного топлива с различными физико-химическими характеристиками. Показана монотонная зависимость резонансной длины волны от показателя преломления и возможность различения стандартного и арктического дизельного топлива. Средняя чувствительность датчика составила 13300 нм на единицу показателя преломления. Обсуждены возможности и ограничения применения метода для контроля качества топлива.

Ключевые слова: волоконно-оптический датчик; поверхностный плазмонный резонанс; ППР; качество дизельного топлива; измерение показателя преломления