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A Novel All-Optical Photonic Crystal Sensor for Petrochemical Liquid Detection

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Abstract: In this study, we introduce a novel and innovative optical sensor based on photonic crystals designed for the detection of petrochemical liquids. This device leverages the unique properties of photonic crystals to provide exceptional sensitivity and measurement accuracy. The sensor comprises a square lattice of gallium arsenide (GaAs) rods suspended in air and coupled to an optimized ring resonator. This compact architecture, measuring only 274 μm^2, enables the sensor to be easily integrated into miniaturized systems. The interaction of petrochemical liquids such as petrol, kerosene, or diesel with the sensor induces changes in its optical properties. These variations, measured by analyzing the transmitted light, allow for the precise identification and quantification of the substances present in the sample. This approach offers rapid and reliable detection, opening up new prospects in industrial quality control, environmental monitoring, and safety. The strengths of this sensor lie in its high sensitivity, enabling the detection of trace amounts of contaminants, and its extremely short response time, ideal for real-time monitoring. Moreover, its fabrication relies on well-established processes, promising large-scale production at a competitive cost. The potential applications of this sensor are numerous and could revolutionize detection methods in the petrochemical industry.

Keywords: Petrochemical, Photonic crystal resonator, Sensors, Optical circuits.

Introduction

The rise of the automotive industry has led to increased consumption of petrochemical products, such as diesel and gasoline. Consequently, the quality of fuel used in a motor vehicle affects its longevity. Inferior, or impure, fuel not only impairs engine performance but also poses a significant environmental risk. The use of inferior quality fuels in automobiles significantly contributes to the increase in carbon dioxide (CO_2) emissions, a major air pollutant that exacerbates global warming (Chiang et al., 1996; Florides & Christodoulides, 2009). Therefore, it is imperative that the scientific community develop an effective mechanism for the detection of pure petrochemical products. Although several technologies have been identified in this area, including techniques based on the evaluation of physico-chemical properties: density, viscosity, odor, color, etc. and analytical methods such as chromatography, titration and ultrasonic techniques (Shahru Bahari et al., 1992; Gupta & Sharma, 2010; Sadat, 2014), the latter present limitations in terms of complexity, cost, speed, sensitivity and accuracy.

Interest in photonic crystal (PhC)-based sensors has grown significantly over the past decade due to their exceptional potential for detecting a wide range of parameters, including temperature (Elhachemi et al., 2022), pressure (Elhachemi & Leila, 2023), electromagnetic fields (Chabani et al., 2024), glucose (Iman et al., 2022),

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cancer cells (Panda et al., 2023), liquids and chemical compounds (Yang et al., 2024). Unlike conventional sensors, photonic crystal devices are distinguished by their easily tunable optical properties, which gives them increased adaptability for specific detection applications. In addition, the possibility of selectively introducing liquids or chemical compounds into the structure of photonic crystals induces efficient light-matter interactions, a considerable advantage for the detection of liquids and chemical compounds (Yang et al., 2024). In order to meet the critical need for the detection of petrochemical products, we propose a novel design of optical sensor based on the use of two-dimensional photonic crystals. This innovative approach aims to optimize the sensitivity of the detection of liquid samples of petrochemical products by focusing on the miniaturization of the device, the improvement of the response time and the simplification of its manufacture.

Detection Principles for Petrochemical Sensors

In the petrochemical sector, sensors play a crucial role in the precise analysis of the composition of fluids used. These sensors are based on the principle of photonic resonance in ring resonator structures. The objective of this text is to provide an in-depth analysis of the principle of photonic resonance, explaining the fundamental concepts and mechanisms that govern it. Photonic resonance occurs when a light wave is confined within a ring resonator whose dimensions are on the order of its wavelength. This phenomenon generates distinct resonance modes, each defined by a specific wavelength and quality factor (Q).

The resonance wavelength is strongly influenced by the refractive index of the material constituting the structure, as well as its geometric configuration. The refractive index (RI) is a dimensionless quantity that characterizes the ability of a medium to deviate light. It is defined as the ratio between the speed of light in a vacuum and its speed in the medium under consideration. Liquid hydrocarbons derived from petroleum, such as petrol, kerosene, and diesel, exhibit distinct refractive indices that allow their identification. Each liquid hydrocarbon possesses a unique RI, which constitutes a reliable method of identification, as illustrated in the table below (Kumar et al., 2024; Hossain et al., 2023).

Table 1. Refractive index for petrol, kerosene and diesel

Petrochemical liquid	Refractive index (RI)
Petrol	1.418
Kerosene	1.44
Diesel	1.46

Basic Structure and Analysis of Photonic Properties

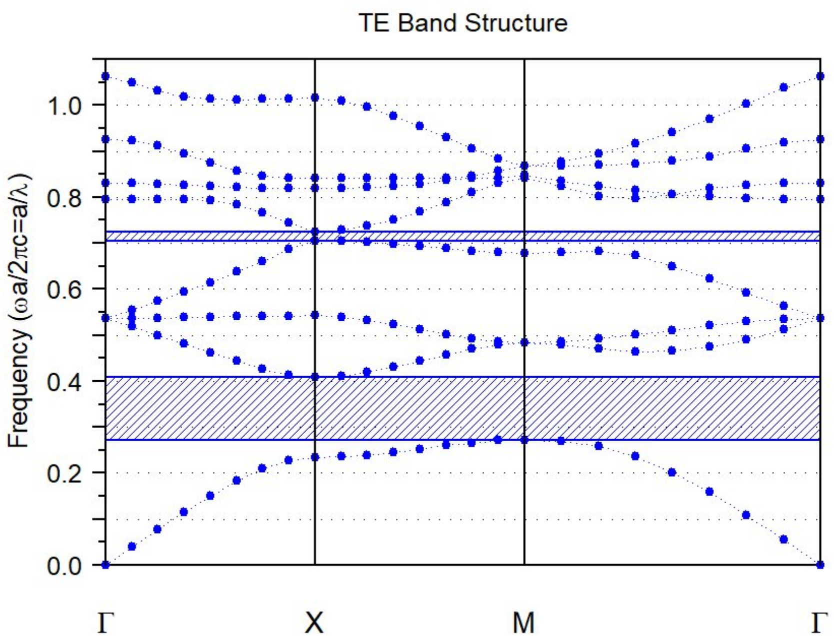

Figure1. The fundamental PhC band structure

This photonic device is fundamentally comprised of a two-dimensional, square lattice of free-standing Gallium Arsenide (GaAs) rods within an air matrix (refractive index n = 1). The array consists of 29 rows and 29 columns of rods. The inter-rod spacing, or period (a), is 0.5635 µm, measured along the X and Z axes. Each rod possesses a radius (r) equal to 0.2a.

The optical properties of the structure, specifically light propagation and confinement were investigated using the plane wave expansion (PWE) method. This numerical analysis, employing optimized structural parameters, facilitated the calculation of the structure's photonic bandgaps (PBGs) and propagation modes. The results of this analysis are presented in Figure 1.

The structure demonstrates two distinct photonic band gaps (PBGs) for transverse electric (TE) polarized modes. The first PBG spans from 0.268 to 0.414 a/λ, equivalent to wavelengths of 1361.11 nm to 2102.61 nm. The second PBG ranges from 0.7 to 0.728 a/λ, corresponding to wavelengths of 774 nm to 805 nm. Notably, the first TE-mode PBG (1361.11 nm to 2102.61 nm) coincides precisely with the low-loss third optical window of Gallium Arsenide (GaAs). This spectral alignment renders the proposed structure highly advantageous for its intended application in petrochemical sensing.

Petrochemical Liquid Sensor Design

A Gaussian optical signal with a central wavelength of 1550 nm is initially injected into the input port of an optimized ring resonator. The device is designed to favor the exclusive transmission of this specific wavelength while attenuating others. The signal passes through the resonator in an air medium, in the absence of petrochemical liquids, and is collected at the output port. The output spectrum analysis is performed by applying the Fast Fourier Transform (FFT) to the Gaussian signal recorded and stored by a sampling oscilloscope (represented in green) (Figure 2a and 2b). The Finite-Difference Time-Domain (FDTD) method is employed to simulate the normalized transmission spectrum at the resonator output in the presence of various petrochemical liquids introduced on the sensor (Rsoft Design Group, 2014). This approach allows evaluating the influence of these substances on the transmission properties of the resonator and characterizing its sensitivity to the detection of petrochemical liquids.

Evaluation of the performance of petrochemical liquid sensors is crucial to ensure their reliability and efficiency in various industrial applications. A key parameter in this evaluation is the quality factor Q, which reflects the sensor's ability to discriminate between different wavelengths of the light spectrum. This quality factor is defined as the ratio of the resonance wavelength (λ) to the full width at half maximum (FWHM) of the wavelength spectrum (Δλ). The quality factor Q can be calculated using the following equation:

$$Q = \lambda / \Delta\lambda \tag{1}$$

Where: λ represents the resonance wavelength of the sensor

Δλ corresponds to the full width at half maximum of the wavelength spectrum

This equation allows the quantification of the sensor's ability to detect subtle variations in the composition of petrochemical liquids, based on their refractive index. Measurement of the quality factor Q is essential to evaluate the sensor's sensitivity and accuracy in the detection of petrochemical liquids. A high-quality factor indicates better spectral resolution, thus enabling more precise identification of the components present in the samples analyzed.

Furthermore, the quality factor provides a reliable indication of the sensor's performance in specific applications, such as quality control of petroleum products or contaminant detection in fuels. The quality factor Q is frequently used to evaluate energy storage and losses within a ring resonator. An increase in the value of Q is manifested by a sharply pronounced peak at the resonance wavelength, thus illustrating a direct proportional and inversely proportional relationship with energy storage and losses, respectively. Therefore, the acquisition of the quality factor from the proposed petrochemical liquid sensor is important in this field.

Our study demonstrates that the resonance wavelength of each petrochemical liquid (petrol, kerosene, and diesel) exhibits a shift towards higher values, indicating an enhanced sensitivity for each liquid. The performance of the microstructure-based optical sensor is quantitatively evaluated by the sensitivity to the refractive index of each liquid. This sensitivity is defined as the ratio of the resonance wavelength shift to the refractive index variation of the injected liquid (Mallika et al., 2015):

$$S = \Delta\lambda / \Delta n \quad (2)$$

Where $\Delta\lambda$ represents the resonance wavelength shift, and Δn corresponds to the refractive index variation for each petrochemical product.

In general, an increase in the sensitivity to the refractive index of each petrochemical liquid induces significant shifts in the resonance wavelength as a function of these index variations. Within the scope of this study, the ring resonator micro-sensor exhibits a particularly high sensitivity to the refractive index of petrochemical liquids, reaching approximately 1334 nm/RIU (Refractive Index Unit). For each petrochemical liquid analyzed, Figure 3 and Table 2 summarize the performance parameters of our petrochemical sensor, including resonance wavelength, normalized transmission efficiency, quality factor, and sensitivity.

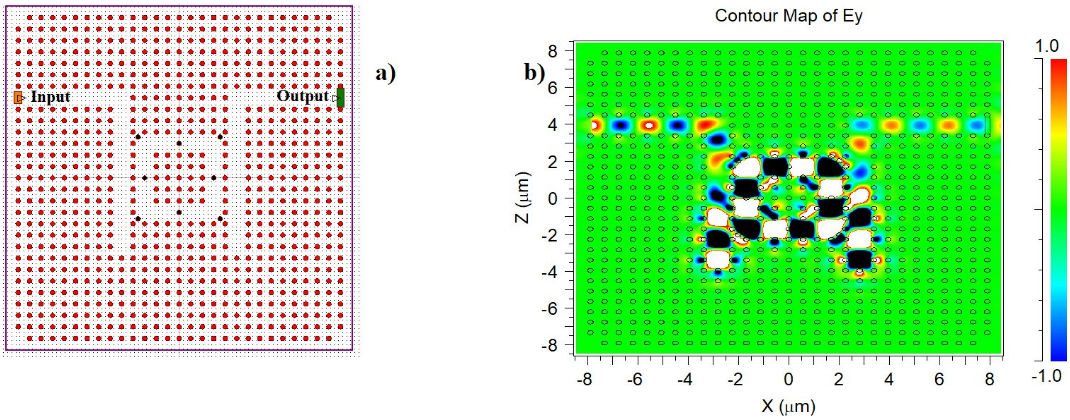

Figure 2. Proposed layout of the petrochemical liquid sensor

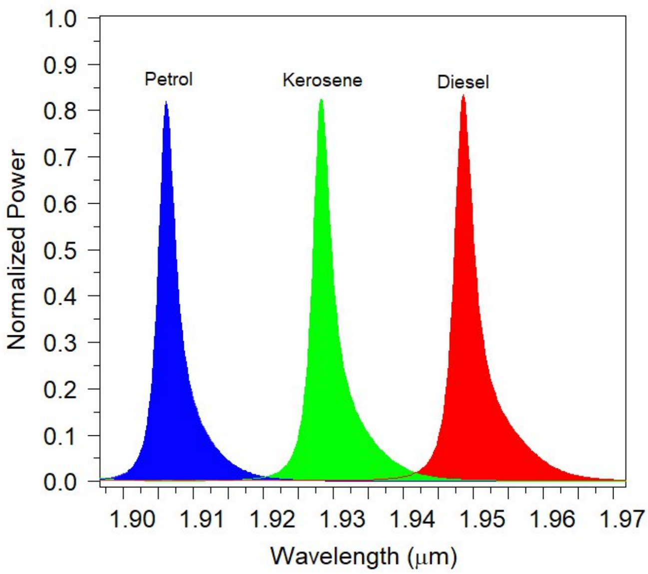

Figure 3. Study of the normalized resonance spectrum of a petrochemical liquid sensor

Table 2. Functional characterization of a petrochemical sensor

Petrochemical liquid	Refractive Index (RIU)	Resonant Wavelength (nm)	Transmission Efficiency (%)	Quality factor	Sensitivity (nm/ RIU)
Petrol	1.418	1906.1	82	705	1344
Kerosene	1.44	1928.3	82.4	664	1339
Diesel	1.46	1948.6	83.4	608	1334

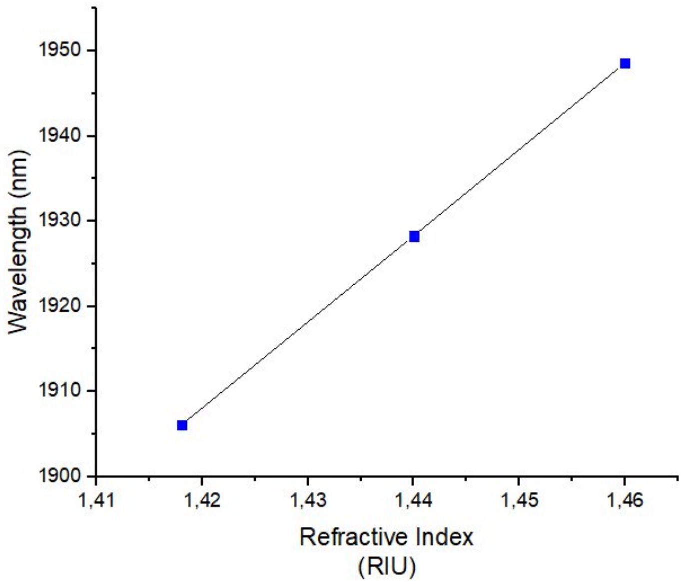

Figure 4. Interaction between the resonant wavelength and the refractive index of petrochemical

Consequently, the illustration provided in Figure 4 highlights the linear correlation between resonance wavelengths and the refractive index of petrochemical compounds. The collected data confirms the enhanced effectiveness of our petrochemical sensors using a ring resonator compared to conventional sensors currently available.

Conclusion

In the framework of our work, we propose a novel all-optical photonic crystal-based sensor for the detection of petrochemical liquids. The operating principle relies on the injection of various petrochemical products, such as petrol, kerosene, and diesel, into the sensor. The sensor's performance was numerically evaluated using two methods: Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD). This sensor exhibits high sensitivity, an ultra-compact size of 274 μm^2, and a response time on the order of the picosecond, which corresponds to a very high data rate, on the order of the terahertz. The proposed sensor, adaptable to integrated optics, industry, and nanotechnology-based sensing applications, offers several advantages.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

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Conflict of Interest

* The authors declare that they have no conflicts of interest

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References

Chiang, P. C., Chiang, Y. C., Chang, E. E., & Chang, S. C. (1996). Characterizations of hazardous air pollutants emitted from motor vehicles. *Toxicological & Environmental Chemistry, 56*(1-4), 85-104.

Chabani, S. B., Dekkiche, L., Kouddad, E., & Hassani, I. (2024). A novel proposal of an electro-optical sensor to measure various levels of an electric field using pockels effect photonic crystals. *Journal of Nanoelectronics and Optoelectronics, 19*(6), 665-668.

Elhachemi, K., & Leila, D. (2023). High-sensitivity all-optical pressure sensor based on photonic-crystal nanotechnology. *Journal of Russian Laser Research, 44*(3), 284-288.

Elhachemi, K., Leila, D., & Rafah, N. (2022). High sensitivity and ultra-high-quality factor for an all-optical temperature sensor based on photonic crystal technology. *Nano Tech Nano Sci Ind J, 16*(6), 174.

Florides, G. A., & Christodoulides, P. (2009). Global warming and carbon dioxide through sciences. *Environment International, 35*(2), 390-401.

Gupta, A. K., & Sharma, R. K. (2010). A new method for estimation of automobile fuel adulteration. *Air Pollution, 10*, 10054.

Hossain, M. B., Kříž, J., Dhasarathan, V., & Rahaman, M. E. (2023). Photonic crystal fiber (PhCF) for petrochemical sensing. *Frontiers in Physics, 10*, 1097841.

Iman, O., Samia, D., & Benattou, F. (2022, May). All optical biosensors for glucose and urea detection based on photonic crystal nano-technology. In *2022 7th International Conference on Image and Signal Processing and their Applications (ISPA)* (pp. 1-5). IEEE.

Kumar, V., Raghuwanshi, S. K., & Kumar, S. (2024). Nanocomposite thin film-based surface plasmon sensor for detection of ethanol in petrochemical industries. *IEEE Transactions on Plasma Science*.

Mallika, C. S., Bahaddur, I., Srikanth, P. C., & Sharan, P. (2015). Photonic crystal ring resonator structure for temperature measurement. *Optik, 126*(20), 2252-2255.

Panda, A., Van Nguyen, C., Pukhrambam, P. D., & Dhasarathan, V. (2023). Employing metamaterial and Ti3C2Tx (MXene) material for cancer cells detection using defective 1D photonic crystal. *Optical and Quantum Electronics, 55*(5), 480.

Sadat, A. (2014). Determining the adulteration of diesel by an optical method. *International Journal of Computer Applications, 100*(13).

Shahru Bahari, M., Criddle, W. J., & Thomas, J. R. (1992). Fuel cell methodology for determining petrol adulteration with kerosene. In *Analytical Proceedings* (Vol. 29, No. 1, pp. 30-31).

Yang, Y., Yu, L., Jiang, X., Li, Y., He, X. W., Chen, L., & Zhang, Y. (2024). Recent advances in photonic crystal-based chemical sensors. *Chemical Communications*, *69*: 9177-9193.

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