Egypt. J. Chem. **Vol. 69**, No.2 pp.189 - 195 (2026)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

A Novel 2D Photonic Crystal Nanotechnology Design for Petrochemical Detection

Sououdi Boumediene Chabani,[1,2], Elhachemi Kouddad,[1,3*] Islam Hassani,[1,4] , Roqiya Baya,[1]

[1] *Department of Electrical Engineering, Faculty of Science and Technology. University of Adrar 01000, Algeria*

[2] *Laboratory of Energy, Environment and Information Systems, University of Adrar 01000, Algeria*

[3] *Telecommunication and Digital Signal Processing Laboratory, Faculty of Electrical Engineering, Department of Telecommunications, University Djillali Liabes, Sidi-Bel-Abbes 22000, Algeria*

[4] *Sustainable Development and Informatics Laboratory (LDDI), University of Adrar, Algeria*

[*] *Corresponding author: Elhachemi Kouddad, Email: elh.kouddad@univ-adrar.edu.dz*

Abstract

In this article, we propose a novel all-optical sensor based on photonic crystals for the detection of petrochemical liquids. The sensor is based on a square lattice of GaAs rods suspended in air, coupled by an optimized ring resonator. The sensor performance was evaluated by injecting various petrochemical products, such as petrol, kerosene, and diesel. The sensor exhibits high sensitivity, high transmission, ultra-compact size of 274 μm², very fast response time, and high throughput. These characteristics make this sensor a promising candidate for various petrochemical detection applications.

Keywords: Photonic crystal resonator, petrochemical, PWE method, FDTD method, optical circuits, sensor.

1. 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 directly impacts a motor vehicle's 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. [1, 3]

Therefore, it is imperative that the scientific community develops 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 [4, 5], 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 [6,8], including temperature [9], pressure [10], electromagnetic fields [11], glucose [12], cancer cells [13], liquids and chemical compounds [14]. 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 [14].

While various techniques exist [4, 5], they often suffer from limitations in terms of complexity, cost, speed, sensitivity, and accuracy. Addressing these challenges, our novel 2D photonic crystal design offers a promising alternative. Its intrinsic properties allow for ultra-compact device size, rapid response times (picoseconds), and high sensitivity (1334 nm/RIU), features crucial for real-time, portable, and efficient petrochemical detection. Furthermore, the inherent simplicity of fabricating such photonic crystal structures makes our proposed sensor highly attractive for industrial implementation.

2. Detection Principles and Key Performance Metrics for Petrochemical Sensors

In the petrochemical sector, sensors play a crucial role in the precise analysis of fluid composition.

*Corresponding author e-mail: elh.kouddad@univ-adrar.edu.dz ; (Elhachemi Kouddad).

Received date: 20/05/2025; Revised date here: 25/06/2025; Accepted date here 03/08/2025

DOI: 10.21608/EJCHEM.2025.387220.11797

Our proposed sensor operates on the principle of photonic resonance within a ring resonator structure. This phenomenon occurs when a light wave is confined within a resonator whose dimensions are comparable to its wavelength, generating distinct resonance modes defined by a specific wavelength (λ) and quality factor (Q). The resonance wavelength is highly sensitive to the refractive index (RI) of the surrounding medium and the geometric configuration of the structure. The refractive index, a dimensionless quantity, characterizes a medium's ability to refract light, defined as the ratio of light speed in vacuum to its speed in the medium. Significantly, various liquid hydrocarbons derived from petroleum, such as petrol, kerosene, and diesel, exhibit unique refractive indices, enabling their distinct identification, as detailed in Table 1[15, 16]:

TABLE 1. Refractiveindex for Petrol,KeroseneandDiesel

Petrochemical liquid	Refractive index (RI)
Petrol	1.418
kerosene	1.44
diesel	1.46

The quality factor (Q) is a critical metric for evaluating sensor performance, reflecting its ability to discriminate between different wavelengths and indicating energy storage and losses within the resonator. A higher Q-factor signifies better spectral resolution and more precise identification of components. It is quantitatively defined as the ratio of the resonance wavelength (λ) to the full width at half maximum (FWHM) of the wavelength spectrum (Δλ):

$$Q = \lambda / \Delta\lambda \qquad (1)$$

Another essential parameter is the sensitivity (S) to the refractive index, which quantifies the sensor's response to changes in the injected liquid's composition. It is defined as the ratio of the resonance wavelength shift (Δλ) to the refractive index variation (Δn) of the liquid:

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

An increase in sensitivity leads to more significant shifts in the resonance wavelength, enabling effective detection of variations in petrochemical liquid properties.

3. Basic Structure and Analysis of Photonic Properties

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.

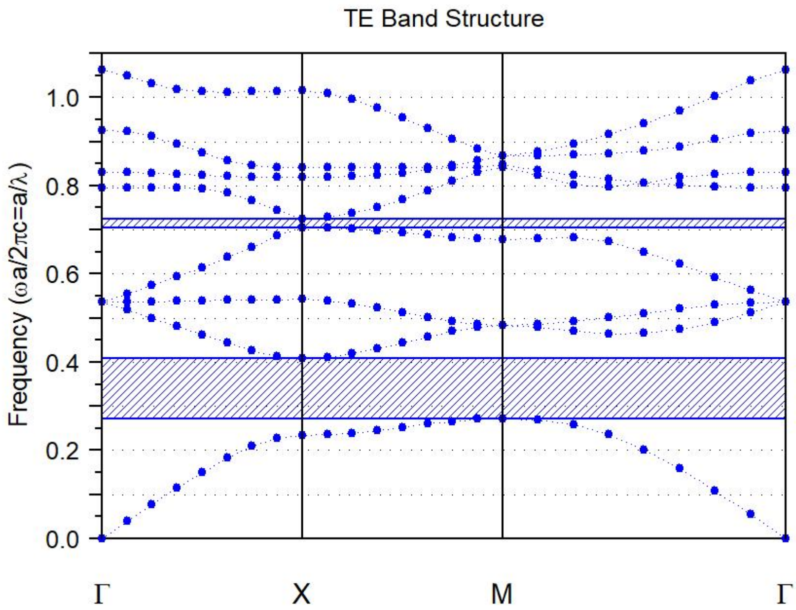


Fig.1: The fundamental PhC band structure.

4. 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 [17]. 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. The quality factor (Q) and sensitivity (S) were calculated using Equations (1) and (2) respectively, to evaluate the sensor's performance. The results are summarized in Table 2.

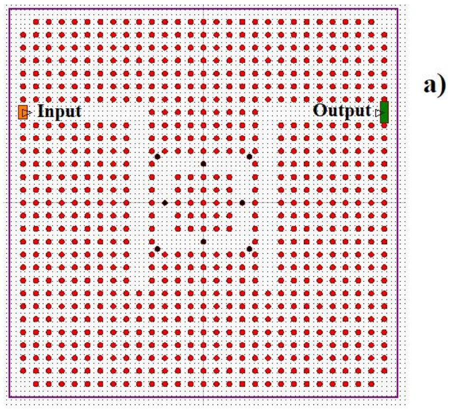
This equation allows the quantification of the sensor's ability to detect subtle variations in the composition of petrochemical liquids, based on their refractive index.

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 analyzed samples.

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 directly 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 of significant importance 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.

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.



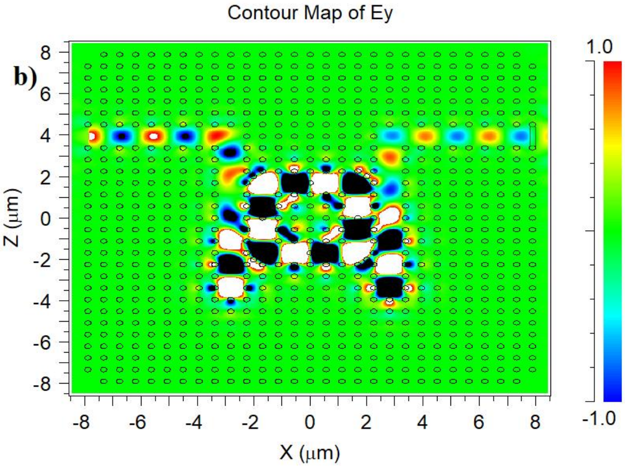


Fig.2: Proposed Layout of the Petrochemical Liquid Sensor

Functional Characterization and Discussion of Sensor Performance

Table 2 provides a comprehensive functional characterization of the proposed optical sensor for petrochemical liquid detection, summarizing the performance obtained for petrol, kerosene, and diesel.

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

A direct and linear correlation is observed between the refractive index (RI) of the petrochemical liquid and its corresponding resonant wavelength. As the RI increases from 1.418 for petrol to 1.46 for diesel, the resonant wavelength systematically shifts towards higher values, ranging from 1906.1 nm for petrol to 1948.6 nm for diesel. This behavior confirms the sensor's high sensitivity to even subtle variations in the samples' refractive index, which is fundamental for the precise identification of different petrochemical products. This linear relationship is visually confirmed by Figure 4.

The sensor consistently maintains a remarkably high transmission efficiency, ranging between 82% and 83.4% for all tested liquids. Such high transmission efficiency is crucial as it ensures that the output signal is sufficiently strong for reliable detection and accurate analysis, thereby minimizing signal losses and enhancing the system's signal-to-noise ratio.

The quality factor (Q) varies from 705 for petrol to 608 for diesel. While these values are notably high, a slight decrease in the Q-factor is observed as the refractive index of the liquid increases. A high Q-factor signifies the sensor's excellent ability to confine light and produce sharp, narrow resonance peaks, which is essential for high spectral resolution and precise discrimination between different wavelengths. The marginal reduction in Q for higher RIs could potentially be attributed to increased energy losses due to stronger evanescent field interaction with the higher-index liquids, a consideration for future optimization efforts.

The sensor exhibits a consistently high sensitivity around 1334 nm/RIU (Refractive Index Unit), specifically ranging from 1344 nm/RIU for petrol to 1334 nm/RIU for diesel. This particularly high sensitivity indicates that even minor modifications in the liquid's refractive index result in significant and easily measurable shifts in the resonance wavelength. This characteristic is paramount for the rapid and reliable detection of impurities or adulterations in petrochemical products.

In summary, the results presented in Table 2 confirm that the proposed photonic crystal sensor design demonstrates exceptional performance in terms of both sensitivity and transmission efficiency. The clear linear correlation between the refractive index and the resonant wavelength, coupled with the high sensitivity (achieving up to 1344 nm/RIU), positions this sensor as a highly promising solution for accurate and reliable petrochemical liquid detection in various industrial and environmental applications.

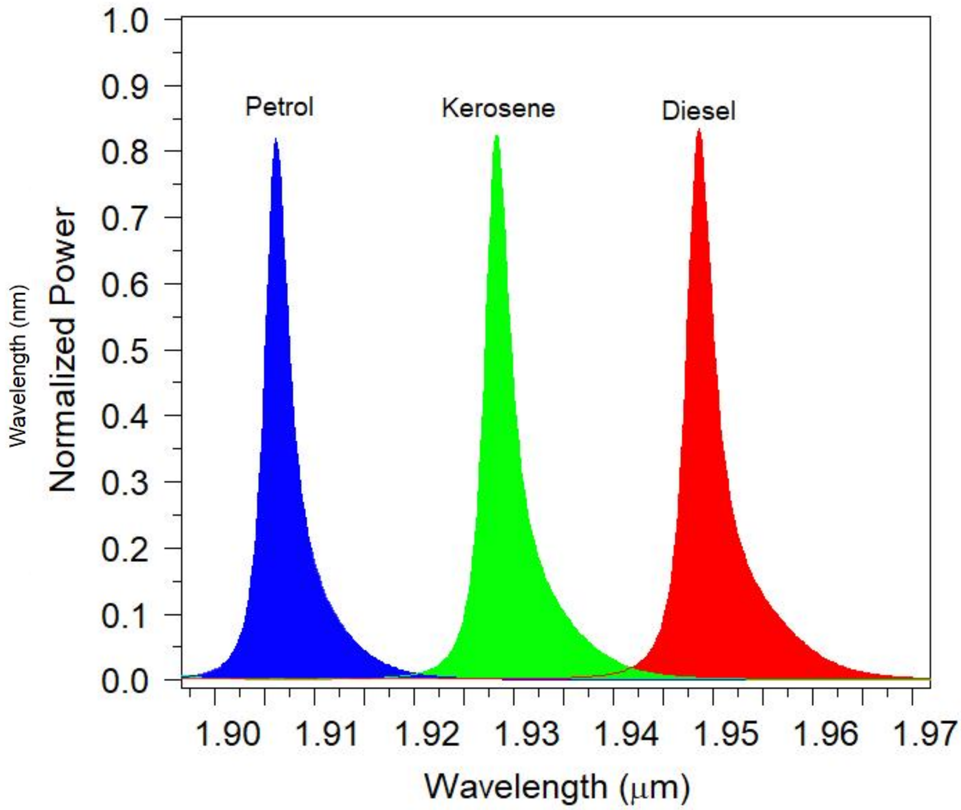


Fig.3: Study of the normalized resonance spectrum of a petrochemical liquid sensor.

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 sensor using a ring resonator compared to conventional sensors currently available.

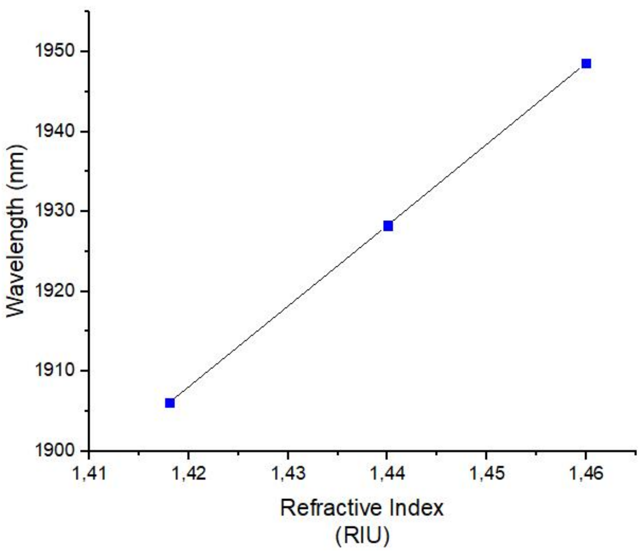


Fig.4: Interaction between the resonant wavelength and the refractive index of petrochemical

The impressive performance characteristics of our sensor, particularly its high sensitivity and ultra-compact size, open up numerous practical applications. In industrial settings, it could enable real-time, on-line quality control of fuels, ensuring compliance with standards and preventing the use of adulterated products. For environmental protection, the sensor offers a rapid and accurate means of detecting petrochemical spills in critical ecosystems or monitoring emissions from industrial facilities, facilitating timely intervention and minimizing ecological damage. Furthermore, its potential for integration into miniaturized, portable devices makes it ideal for field diagnostics, allowing for on-site analysis without the need for complex laboratory equipment. These capabilities underscore the significant societal relevance of our work in ensuring fuel quality, protecting the environment, and enhancing public safety.

Our immediate future work will focus on the experimental fabrication and validation of the proposed sensor design to confirm its performance characteristics under real-world conditions.

5. 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.

Conflicts of interest

There are no conflicts to declare

Acknowledgment

This work was supported by the Directorate General for Scientific Research and Technological Development (DGRSDT).
Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

1. 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.
2. Mansour, M. S., Abdel-Shafy, H. I., & Ibrahim, A. M. (2024). Petroleum wastewater: Environmental protection, treatment, and safe reuse: An overview. Journal of environmental management, 351, 119827.
3. Mansour, M. S., Abdel-Shafy, H. I., & Ibrahim, A. M. (2025). Zero liquid discharge of petrochemical industry wastewaters via environmentally friendly technologies: An overview. Egyptian Journal of Petroleum, 34(1), 6.
4. Mohamed, A., Nassar, M., El-Olemy, A., & Emara, M. (2022). A Stability Indicating Method for Determination of Odevixibat using High Performance Liquid Chromatography Method. Egyptian Journal of Chemistry, 65(10), 203-208.
5. Sadat, A. (2014). Determining the adulteration of diesel by an optical method. International Journal of Computer Applications, 100(13).
6. Darwesh, O., & Matter, I. (2022). Challenges of nanotechnology applications in addressing environmental pollution. Egyptian Journal of Chemistry, 65(2), 275-285.
7. Ahmed, E. H., & Ayoub, M. M. (2024). Investigation and Characterization of Physical Properties and Phonon modes of ZnO/PVA/PANI for Photonic Crystals application. Egyptian Journal of Chemistry, 67(10), 383-388.
8. Abdel-Shafy, H. I., & Mansour, M. S. (2018). Green synthesis of metallic nanoparticles from natural resources and food waste and their environmental application. Green metal nanoparticles: Synthesis, characterization and their applications, 321-385.
9. Elhachemi K., Leila D., Rafah N. High Sensitivity and Ultra-High-Quality Factor for an all-Optical Temperature Sensor Based on Photonic Crystal Technology. Nano Tech Nano Sci IndJ.2022;16(6):174
10. 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.
11. 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.
12. 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.
13. 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.
14. 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.
15. 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.
16. Hossain, M. B., Kříž, J., Dhasarathan, V., & Rahaman, M. E. (2023). Photonic crystal fiber (PhCF) for petrochemical sensing. Frontiers in Physics, 10, 1097841.
17. In this paper, Fullwave commercial software developed by Rsoft Design Group (http://www.rsoftdesign.com) is used for linear and nonlinear FDTD simulations, v.2014.09, license 16849450.