Medical Technologies Journal, Volume: 2, Issue: 4, October-December 2018, Pages: 293-300. Doi : https://doi.org/10.26415/2572-004X-vol2iss1p293-300

Novel Design of Optical Sensor Based on Two-Dimensional Photonic Crystals for the Detection of Volatile Organic Compounds that can Infect Human Health

Type of article: Original

Ghoumazi Mehdi1,2, Abdesselam Hocini1, Messaoud Hameurlain2, Mokhtar Boudaa2
1Laboratoire d'Analyse des signaux et Systèmes, Département d'Electronique, faculté de technologie, Université Mohamed boudiaf de M'Sila, Bp.166, Route Ichbilia, M'Sila 28000, Alegria.
2Unité de Recherche en Optique et Photonique (UROP-Sétif), Centre de Développement des Technologies Avancées (CDTA), Cité 20 Aout 1956 Baba Hassen, Alger, Algérie.

Abstract

Background: In recent research, optical sensors gained a growing interest motivated by the increasing need for specific sensors that allow for routine and effective measurements in several fields and analysis such as, safety, environment, and human health. Among optical sensors are photonic crystal sensors, which are characterized by high sensitivity and biocompatibility. The variations inside and around the photonic crystal can give important information by measuring the wavelength, the band gap, the output power…etc. Through defects created in photonic crystals such as missing rows of holes or rods, light is guided through and the goal is to achieve a very high sensitivity and spatial selectivity to changing superior bulk devices. In this study, we model a new structure of an optical channel drop filter (CDF) based on 2-dimensional photonic crystals to detect volatile organic compounds that can infect human health.

Objective: Detect the variation of the refractive index by fixing the radius (r) at 99.37nm and the lattice constant (a) at 523nm for various volatile organic compounds such as H_2CO, CH_2Cl_2, and C_2Cl_4 with refractive indexes that are: 1.3746, 1.421 and 1.503 respectively in the optical sensor based on photonic crystals for reasons related to the protection of human health.

Methods: The structure is made of square lattice silicon rods immersed in air. The dielectric constant of silicon and air is 11.9716 and 1 respectively. First, we created a cross shape resonator and designed an optical channel drop filter in the heart of the structure; our method is based on plane wave expansion method (PWE) by using MATLAB software and the finite element method (F.E.M) with COMSOL software.

Results: Three volatile compounds have been studied, such as Dichloromethane used as synthesis intermediate by the chemical industry or solvent used in the pharmaceutical or medical industry. Acute inhalation exposure may cause severe optic neuropathy and liver attack (Hepatitis). Then, the Methanal is used to dry or kill the skin taking as an example, the medical treatment of warts. And perchlorethylene is used for the dry cleaning of tissues and for degreasing metals because it is in category 3 carcinogens, toxic to the nervous system and the kidney. These three volatile compounds where introduced and studied in the proposed structure. The results obtained through this study are as follows:

1- diagram of the TM and TE bands of the photonic crystal in a square array of silicon rods embedded in the air,
2- schematic diagram of the filter,
3- distribution of the refractive index along the structure,
4- structure meshing,
5- propagation and transmission for different refractive indices such as methanal (H2CO), dichloromethane (CH2Cl2) and perchlorethylene (C2Cl4).

Conclusion: In this article, we have been able to simulate, analyze and control our proposed structure with MATLAB and COMSOL software based on the finite element method. The results show that for the three volatile organic compounds, the variation of the signal is due to the wavelength of the resonance which is related to the refractive index (n). This can be seen by the small $\Delta\lambda$ between three volatile organic compounds, which is 0.4nm between (H_2CO, C_2Cl_4) and 2.9 nm between (CH_2Cl_2, H_2CO). Thanks to this change, this structure can be used as sensor for the detection of toxic organic pollutants that can infect human health [16].

Keywords: Photonic crystal, finite element method, volatile organic compounds, ring resonator, human health

Medical Technologies Journal, Volume: 2, Issue: 4, October-December 2018, Pages: 293-300. Doi : https://doi.org/10.26415/2572-004X-vol2iss1p293-300

Corresponding author: Mr Ghoumazi Mehdi, Université Mohamed boudiaf de M'Sila, Algeria. Email:g_mehd@yahoo.fr,
Received: 06 July, 2018, Accepted: 02 December, 2018, English editing: 04 January, 2019,Published: 05 January, 2019.
Screened by iThenticate..

1. Introduction

In recent years, a lot of research using photonic crystals as a detection element for sensing was undertaken due their confinement of light and band structure (1).
Photonic crystals used as a sensor have seen massive development in case of a rising demand of sensing applications in several fields such as: security, healthcare and environment (2). These photonic crystals are periodic dielectric structures and good candidates to build different components for compact application systems. The electromagnetic waves with the photonic Bandgap are prohibited to propagate (3) leading to a lot of interesting phenomena, like photonic crystal laser, optical coupler (4), Optical filter (5), optical switching, high quality (Q) cavity(6) and so on. To calculate the dispersion curves of photonic crystal, there are several theoretical and numerical development tools such as: finite-difference time-domain (FDTD) method (7), multiple multipole methods (8), plane wave method (PWM) (9) and Finite element method (FEM). Among these methods, we used finite element method based on COMSOL software.
First, we designed 2D Square lattice of photonic crystals structure and perform theoretical computing using the plane-wave expansion (PWE) method for the modeling of the EM wave propagation inside the PC. Besides, we have also shown the first Brillouin zone, which contains the TM and TE mode (Fig.1 (red section)) (10).

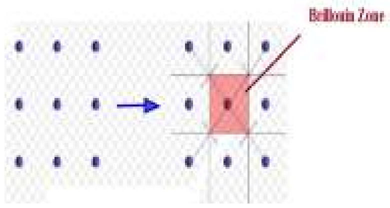


Fig.1. the reciprocal lattices (dots) and corresponding first Brillouin zones of square lattice (10)

In this work, we examine the photonic band structure, propagation use (PWE) and transmission of 2D photonic use by the finite element method (FEM) (11-14) with a commercial software COMSOL Multiphysics® (15).

2. Materials and Methods

Our proposed structure is designed by 31X25 square lattice of dielectric rods embedded in air. The refractive index and the radius of dielectric rods are 3.46 and r=0.19*a respectively. Where 'a' is the lattice constant of the PC structure and its value is 523nm. We applied the finite element method to calculate the dispersion relation of the square lattice pattern for (TM / TE) polarizations. The light propagation is considered in the xy-plane. Fig.2 is showing three photonic band gaps. Next, the simulations will be adjusted to the proposed structure of a channel drop filter (CDF) based on two dimensional photonic crystal ring resonator (PCRR).

As shown in Fig. 2, the two first photonic band gaps (PBGs) in TM mode are with brown color and one in TE mode with purple color. The TM PBGs are in

1215.99 nm< λ< 1809.68nm and 693.26nm< λ< 725.28nm range and the TE PBGs is in 628.07nm < λ< 634.47nm range. We took the first Photonic band gap (PBG) in TM mode where λ is [1215.99, 1809.68] nm this is due to the large width covered by sufficient wavelengths for optical communication applications.

The next step consists in realizing our filter in a fundamental platform as mentioned below: By removing a complete row of dielectric rods in the Γ-M direction to create the bus waveguide and removing some rods in the M-X direction we created the output waveguide. After that, we created across shape resonator between bus and the output waveguide.

The final design of the structure filter is depicted in Fig.3.

The structure consists of two waveguides in horizontal direction (Γ-M) and perpendicular direction (M-X) and a single cross shape of photonic crystal ring resonator (PCRR). The top waveguide is named as bus waveguide and its input port in the left side is marked Port 1 while the other side of the top waveguide is marked Port2. The bottom waveguide is known as dropping waveguide and its output port in below side is marked Port 3.

We observed that the structure driven mechanism could be summarized as follows: from the entrance of the structure, the optical waves pass straight to the port 2. In the meantime, at a desired wavelength, wavelengths go down to the waveguide through a cross shape resonant ring and move to the port 3. Furthermore, we investigate and replace the refractive index of the frame surrounding the resonator by three refractive indices, which belonged to the family of toxic organic pollutants such as: H_2CO, CH_2Cl_2 and C_2Cl_4. The refractive index rods, which changed, is labelled with a blue circle as shown in fig.4.

To define this structure, we used a scalar equation for the transverse electric field component Ez,

$$- [\Delta.E_{z} + (n*k_0)^2] = E_z \qquad (1)$$

Where n is the refractive index and k_0 is the free-space wave number (15).

3. Results

As mentioned above, Fig.2 depicts three photonic forbidden bands (PBGs), two PBGs for the TM mode (brown grid) and one for the TE mode (purple grid) of the photonic crystal in the square array of silicon rods in the air, radius = 0.19a.

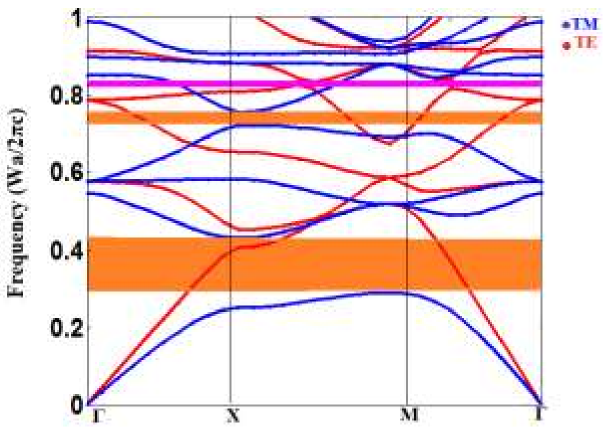
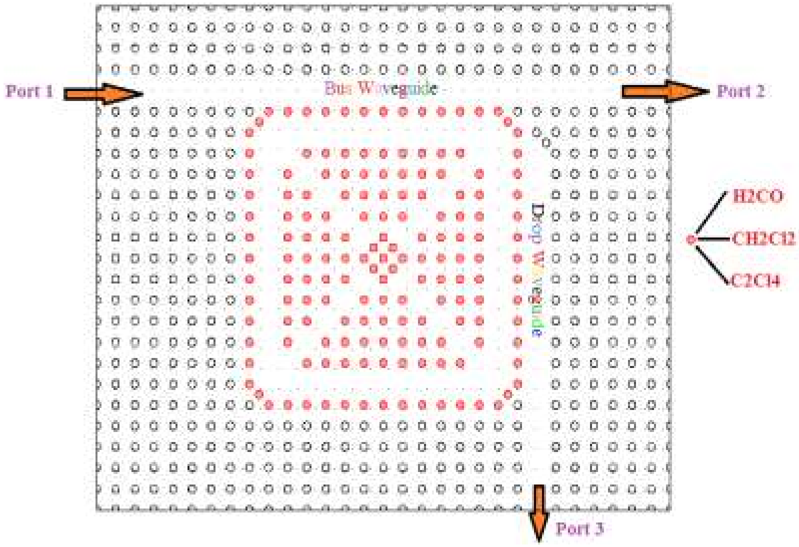


Fig.2. The calculated diagram bands with FEM of TM and TE of the Photonic crystal in the square lattice of Silicon rods in Air, radius=0.19a.

Also, Fig.3 shows the final structure of the filter.



.

Fig.3. The schematic diagram of the filter

Fig.4 years Fig.5 represent the distribution of the refractive index and the mesh along the proposed structure

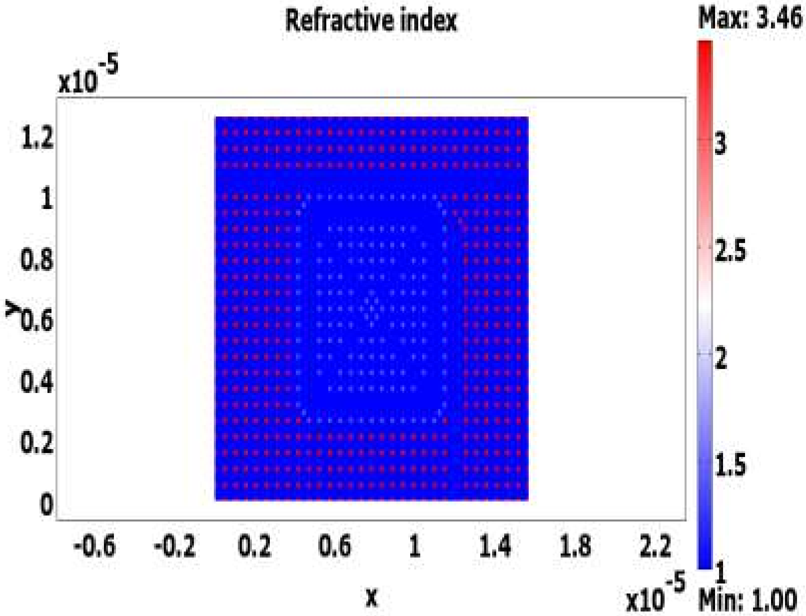


Fig. 4. The distribution of the refractive index in the proposed structure

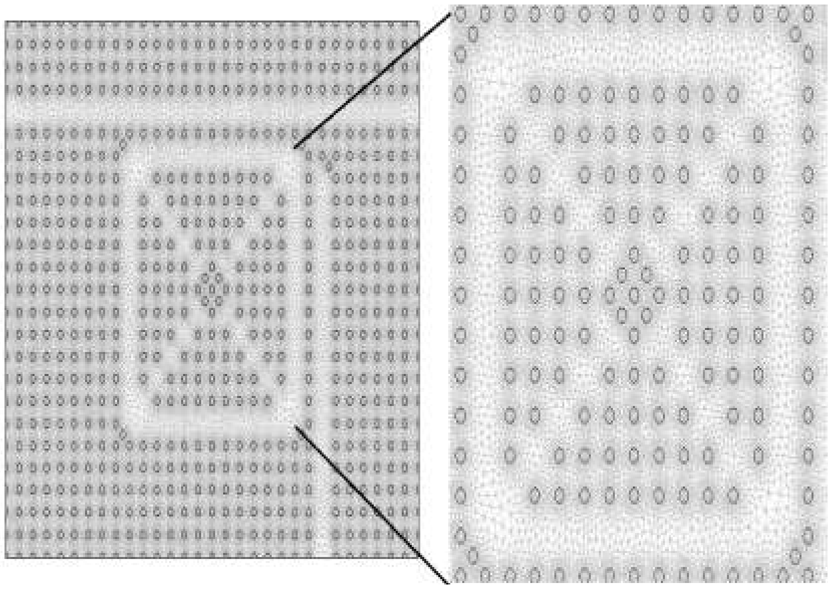


Fig.5 .The proposed structure with mesh

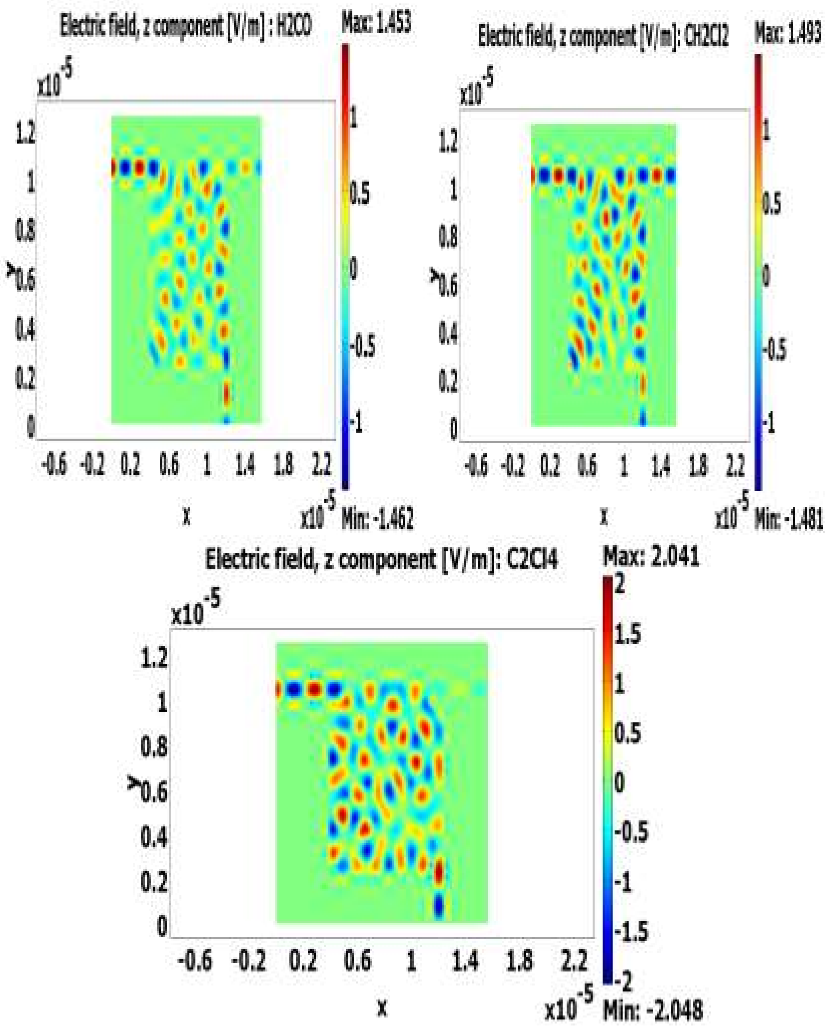


Fig.6. The propagation of the field distribution of the proposed CDF for different refractive index of H2CO, CH_2Cl_2 and C_2Cl_4 respectively at λ = 1550nm

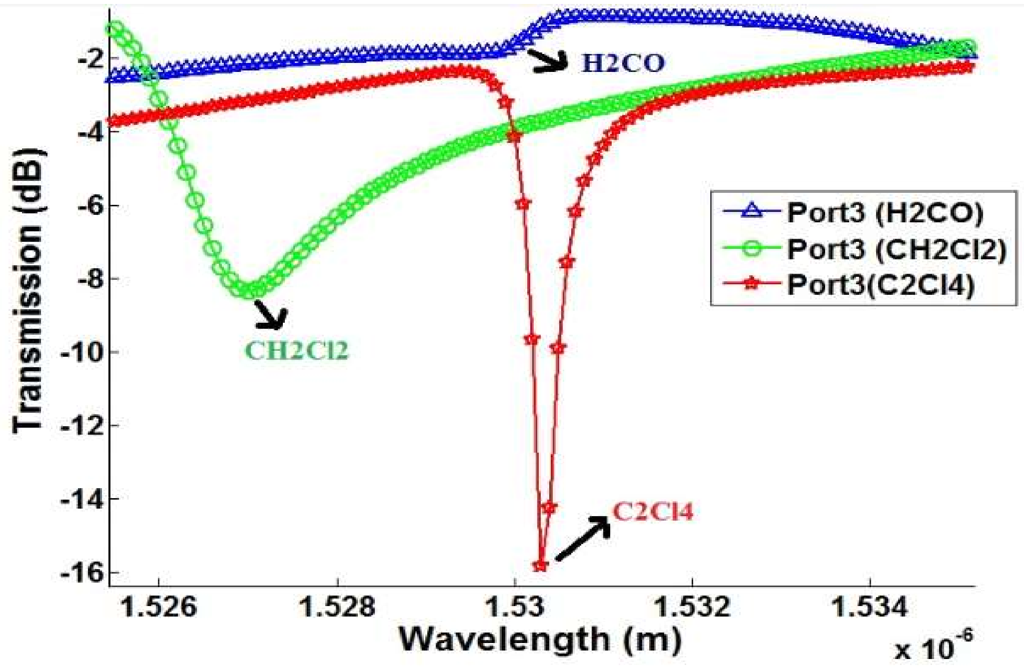


Fig.7. The transmission for different refractive index of H_2CO, CH_2Cl_2 and C_2Cl_4 respectively.

4. Discussion

By using the COMSOL software, we obtained the modeling results from the RF module whose goal is to solve the Maxwell's equations for the distribution of the optical field and to extract the optical properties of the photonic crystals. In this article, we focus our investigation on the influence of the chosen volatile organic compounds materials, such as: H_2CO, CH_2Cl_2 and C_2Cl_4 by changing the refractive index (n) of the frame and the cross shape resonator at the same time (see figure.3 (red color)). From the simulation, we released the distribution of the electric field component (E) and the transmission of three volatile organic compounds (H_2CO, CH_2Cl_2 and C_2Cl_4) in the structure (see Fig. 6). Realizing that the spread is on the (xy) plane, the transmission range of the magnetic field is appeared in Fig.7 for a wavelength, which changes from 1.52 µm up to 1.54µm which is an interim related with the PBGs figured by the plane wave technique (PWE) as it was mentioned in the principal area.

In Figure 7, the transmission in dB of the structure is represented by port 3 for the three volatile organic compounds (H2CO, CH2Cl2 and C2Cl4) whose curves are respectively blue, green and red. It can be seen that for the different materials used, the transmission coefficient reaches maximums at the resonance wavelength. In the case of H2CO, we observe that the transmission coefficient reaches the value of -1.7486 dB for a wavelength λ = 1529.9nm. Then, for CH2Cl2 it is -8.3274 dB for a wavelength of 1527nm and for the last material C2Cl4 the transmission coefficient completes a value of -15.8246de the wavelength λ = 1530.3nm.

Note that the three transmission coefficients that we were able to obtain are classified as follows: Dichloromethane, methanal, and perchlorethylene, respectively. The difference in resonance wavelength between CH2Cl2, H2CO equal to 2.9nm and between H2CO and C2Cl4 equal to 0.4 nm this is due to the refractive index which varies from one volatile organic compound to another (16).

5. Conclusions

In this summary, a modeling of a photonic crystal filter structure with a cross resonator ring using the finite element method was simulated, analyzed and controlled by the COMSOL software. The results obtained by COMSOL show different attitudes of signal for three volatile organic compound materials (H_2CO, CH_2Cl_2 and C_2Cl_4). This change in signal is due to the resonance wavelength of the filter which depends on the refractive index (n) and which is manifested by a wavelength difference ($\Delta\lambda$) of 0.4 between (H_2CO, C_2Cl_4) and 2.9 nm between (CH_2Cl_2, H_2CO). This structure can be used as a sensor for the detection of toxic organic pollutants that can infect human health.

6. Acknowledgments

The Ministry of Higher Education and Scientific Research of Algeria supported the present work

7. Conflict of Interest

There is no conflict of interest to be declared. All authors contributed to this project and article equally. All authors read and approved the final manuscript.

8. Author's biography

Mehdi Ghoumazi is a Ph.D. student in electronics at Department of Electronics, University of Mohamed Boudiaf of M'sila, Algeria. After received his degree in electronic engineering in instrumentation in 2006 and magister degree (2009) in microelectronics optic and hyper frequency at the University of Constantine Algeria, he started working as researcher at Advanced Technologies Development Center (CDTA) in Setif, since 2014. His researches interests are doped optical fibers, crystal photonic based on optical devices used for sensing.

Abdesselam Hocini received his Ph.D., magister and engineer degrees in electronics instrumentation in 2000, 2002 and 2008, all from Constantine University, Algeria. He is currently an assistant professor in Department of Electronics at University of Mohamed Boudiaf of M'sila, Algeria. His research interests include the design and characterization of photonic devices. In particular, his research concerns sensing, solar cells and realizing advanced functional photonic crystal devices.

Messaoud Hameurlain and Mokhtar Boudaa began working as a research support engineer at the Advanced Technology Development Center (CDTA) in Sétif since 2014.

9. References

1) Benmerkhi A, Bouchemat M, Bouchemat T: Influence of eleptical shaped holes on the sensitivity and Q factor in 2D photonic crystals sensor. Photonics and nanostructures-Fundamentals and Applications. 2016 Jul; Volume 20: 7-17.

2) Benmerkhi A, Bouchemat M, Bouchemat T. Improved sensitivity of the photonic crystal slab biosensors by using elliptical air holes. Optik- International Journal for Light and Electron Optics.2016July;Volume 127(14) : 5682-5687.

3) Olaye S, Dehghani AA: Nano-Pressure using High Quality Photonic Crystal Cavity Resonator. 8th IEEE international Symposium on Communication Systems. Networks and Digital Processing. 2012; 978-1-4577-1473-3.

4) Sevin G, Fowler D, Xu G, Julien FH, Colombelli R, Beere H, Ritchie D: Continuous-wave operation of 2.7 thz photonic crystal quantum cascade lasers. Electronics letters; 2010 Oct28; (46) 22. https://doi.org/10.1049/el.2010.2036

5) Petcu A, Preda l: The Optical Transmission Of One-Dimensional. Romanian Journnal of Physics; 2009 Jun; Volume 54 (5) :539–546.

6) Gong Y, Vučković J: Photonic crystal cavities in silicon dioxide. Applied physics letters 96, 2010 Jan 21; 031107. https://doi.org/10.1063/1.3297877

7) Movahhedi M, Abdipour A, Ceric H, Sheikholeslami A, Selberherr S: Optimization of the Perfectly Matched Layer for the Finite-Element Time-Domain Method. IEEE microwave and wireless components letters. 2007 Jan 8; 17(1):10-12. https://doi.org/10.1109/LMWC.2006.887240

8) Moreno E, Erni D, Hafner C: Band structure computations of metallic photonic crystals with the multiple multipole method. physical revwie B, 2002 Apr 65 (15):155120 -1.

9) Sozuer H S Haus J W: Photonic Bands: convergence problems with the Plane wave methode. Physical Review B.1992 Jun 15; 45(24).https://doi.org/10.1103/PhysRevB.45.13962

10)https://en.wikipedia.org/wiki/Brillouin_zone

11)Jin Y, Zhen-Y, Wu Z, Daouadji A: Numerical modeling of pile penetration in silica sands considering the effect of grain breakage. Finite Elements in Analysis and Design. 2018 May 144:15–29. https://doi.org/10.1016/j.finel.2018.02.003

https://doi.org/10.1016/j.finel.2018.02.003

12)Grbovic A, Mihajlovic D: Practical Apects of finite element method applications in dentistry. Balkan Journal of dental Medecine. 2017Jul 8 .Vol 21(2): 69-77.

13)Whiteley,Jonathan. Finite Element Methods. 1red rev. Mathematical Engineering, Springer International Publishing AG; 2017. XI, 232 p.

14)Dyson AP, Tang Z, Tolooiyan A: Use of stochastic XFEM in the investigation of heterogeneity effects on the tensile strength of intermediate geotechnical materials. Finite Elements in Analysis and Design.2018 Jun; 145: 1–9. https://doi.org/10.1016/j.finel.2018.03.003

https://doi.org/10.1016/j.finel.2018.03.003

15) https://www.comsol.com/

16)Tsai WT: Toxic Volatile Organic Compounds (VOCs) in the Atmospheric Environment: Regulatory Aspects and Monitoring in Japan and Korea. Environments. 2016 Sept 7, 3(4) 23.

https://doi.org/10.3390/environments3030023