Majlesi Journal of Electrical Engineering
Vol. 18, No. 1, March 2024

Design and Optimization of a Photonic Crystal-Based All-Optical XOR Gate Using Machine Learning

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ABSTRACT:
In this article, a two-dimensional photonic crystal-based XOR gate is designed and simulated. For this purpose, an initial two-dimensional photonic crystal structure is chosen and waveguides are created for inputs and outputs. Then, defect rods are selected so that the obtained outputs are approximately consistent with the XOR gate truth table. After that, we will be looking for the best output so that the highest optical power is created for logic 1 and the lowest power in the logical state of 0. For this reason, the simulation is performed for four defect rods and the output is obtained for different the radius of the rods. Then, using the K-Nearest Neighbors algorithm, which is a machine learning algorithm, the best output for logic 0 and also for logic 1 is obtained. The results show that the designed logic gate has high output power in logic 1 and very low power in the logic 0 state.

KEYWORDS: Optical XOR gate, Photonic Bandgap, Photonic Crystal, K-Nearest Neighbors.

1. INTRODUCTION

To increase the information transmission in electronic circuits, a reduction in dimensions and integration of circuits is used. However, over time and with the significant reduction in circuits, it seems that downsizing may face serious challenges. For this reason, researchers need to look for a fundamental solution to increase the speed of electronic chips [1]-[12].

One of the options that has attracted the attention of researchers today is the periodic structures in micrometer dimensions, which are called photonic crystals. These structures are made up of two materials with different refractive indices, which are placed alternately beside each other. That is, their structure is periodic. If this periodicity is in one direction, it is called a one-dimensional photonic crystal. If it occurs in two directions, it is called a two-dimensional photonic crystal, and if it is in three directions, it is called a three-dimensional photonic crystal [13]-[15].

The basic principle of photonic bandgap (PBG) crystals is to create a range of continuous wavelengths that cannot pass through the structure due to the properties of PBG. This means that if these wavelengths encounter the structure, they will be reflected. Using this property, light can be guided along specific paths in photonic crystals, which are called waveguides [16]-[22].

Photonic crystals have many applications in electronics, with the most important being the design of logical gates and circuits. In these circuits, light sources are used at the inputs. Logic 0 and 1 are measured at the output based on the measured optical power. That is, if the power is high, it is defined as logic 1, and if it is low, it is defined as logic 0. To

Paper type: Research paper
https://doi.org/10.30486/mjee.2023.1984121.1111
Received: 12 September 2023; revised: 19 October 2023; accepted: 27 November 2023; published: 1 March 2024
How to cite this paper: F. Parandin, A. Mohamadi, **"Design and Optimization of a Photonic Crystal-Based All-Optical XOR Gate Using Machine Learning"**, *Majlesi Journal of Electrical Engineering*, Vol. 18, No. 1, pp. 1-8, 2024.

obtain a logical gate or circuit with suitable and strong values of 0 and 1, trial and error is used. That is, the selected physical parameters are changed until a suitable result is obtained [23]-[39].

In this article, machine learning is used to obtain and optimize the outputs. For this purpose, data obtained from several simulations are considered as the primary data, and the KNN (K-Nearest Neighbors) regression algorithm is used to find the best output.

2. USING MACHINE LEARNING IN THE DESIGN OF XOR GATE

Nowadays, Artificial Intelligence is applied in most industrial fields, and its learning can be of great help in advancing new technologies. Machine Learning is one of the branches of Artificial Intelligence that provides the system with the ability to learn automatically and without explicit programming. In other words, the goal of Machine Learning is to create intelligent systems that learn from a set of data and experiences and can be used to make systems smarter. The learning process in Machine Learning starts with data as input, and the machine learns to discover patterns in the dataset and make better decisions based on the discovered patterns and insights. In fact, the main goal of this field is to give the machine the ability to learn automatically without human intervention and be able to adjust its actions accordingly.

In Machine Learning, different algorithms can be used to identify patterns and train the system using a large volume of data in a repetitive process to obtain useful information. Machine Learning algorithms use computational and statistical methods to learn directly from the data instead of using a predetermined equation that may act like a model. The efficiency of Machine Learning algorithms improves with an increase in the number of samples and data during the learning process.

In this article, an optical XOR gate is designed using photon crystals, and the inputs and outputs are specified to reach the desired gate by selecting waveguide paths. Then, simulations are performed for several physical parameters, and the best result is obtained using one of the Machine Learning algorithms called KNN (K-Nearest Neighbors) regression, and the structure parameters are determined, which are considered the final structure.

3. OPTIMIZING LOGICAL XOR GATE USING MACHINE LEARNING

For designing an optical XOR gate, a two-dimensional photonic crystal structure with a square lattice made of Si rods in air is used. The lattice constant, which is the distance between the centers of adjacent rods, is chosen to be a = 600 nm, and the radius of the Si rods is r = 120 nm. For the structure to function as the desired gate, four rods are selected as defect rods, and the radius of the rods is denoted by rd. The inputs of the gate are denoted by A and B, and the output is denoted by OUT in Fig. 1.

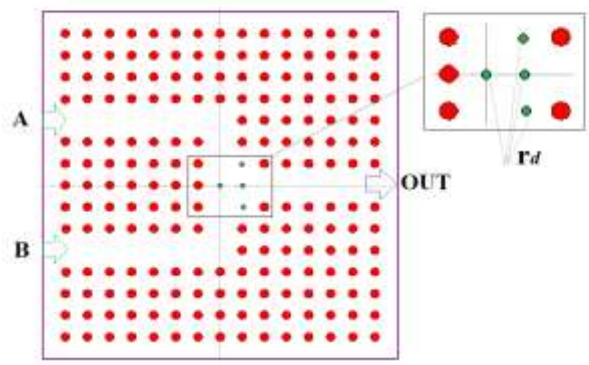

Fig. 1. Proposed structure for XOR gate using a photonic crystal.

Based on the XOR gate truth table, the output is in the logical 1 state only when the inputs are not equal. In other words, if the inputs are equal, the output will be 0. Simulation is performed for a specific value of r_d, and the optical power distribution in the outputs is calculated. The obtained results are shown in Fig. 2. As seen in the figure, the results for equal inputs are almost zero, which is a good result and considered as logical 0 (Fig. 2 a), b)). For unequal inputs, i.e., A=0, B=1, and A=1, B=0, a high power is expected in the output, which is considered as logical 1. In this case, some of the power is directed toward the off-state input path, which reduces the power in the output.

Magnetic polarization is used in this simulation. In other words, this structure has created a photonic band gap for TM modes, and the magnetic waves in the band gap range can be guided in the waveguide paths.

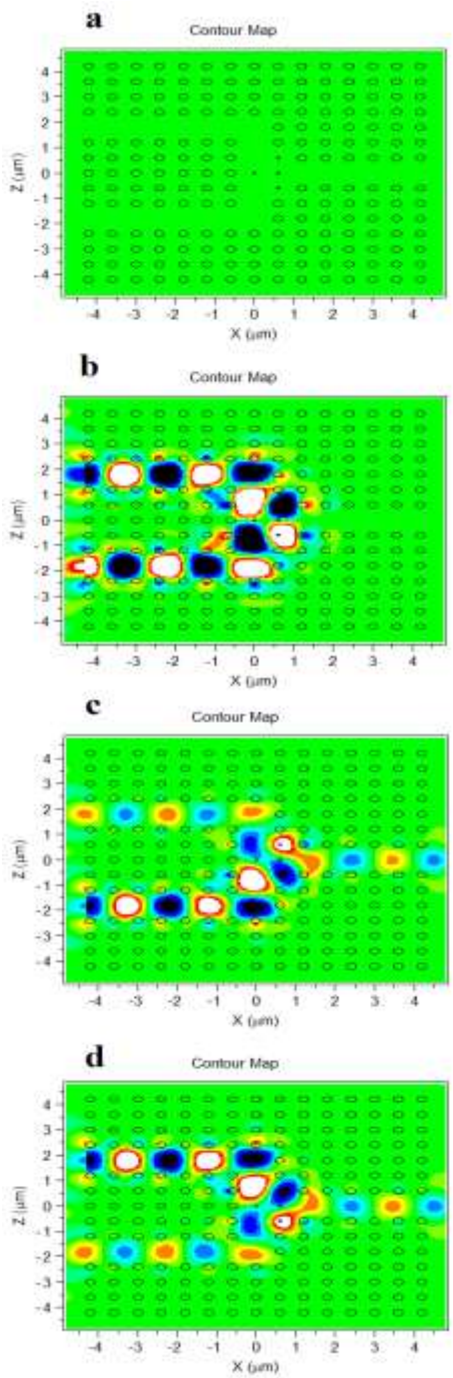

Fig. 2. Power distribution for a) A= B=0, b) A= B=1, c) A=0, B=1 and d) A=1, B=0.

To increase the power in the output, we use machine learning models. For this purpose, simulations are performed for a specific number of r_d values, and the obtained results are selected as the input of the machine learning model. Then, based on the obtained results for each input state, the results are analyzed, and the best working point is determined. The best working point refers to the maximum value when the output is in the logical 1 state and the minimum power value for the logical 0 output.

4. KNN ALGORITHM

K-Nearest Neighbors (KNN) regression is a non-parametric machine learning algorithm used for regression tasks. The algorithm is based on the assumption that data points that are close to each other are likely to have similar output values. Given a new input data point, KNN regression identifies the k-nearest neighbors in the training set and takes the average of their output values as the predicted output for the new data point. KNN regression is a simple yet powerful algorithm that can be used for a wide range of regression tasks. However, it has some limitations such as the need for a large amount of training data, the sensitivity to the choice of the value of k, and the lack of interpretability. Nonetheless, KNN regression remains a popular and effective algorithm for regression tasks in various domains. One of the main advantages is its simplicity and ease of implementation. KNN regression does not require any assumptions about the distribution of the data or the form of the underlying relationship between the variables, making it a versatile method that can be applied to a wide range of problems. Another advantage is that KNN regression can capture nonlinear relationships between the predictor and response variables, which can be missed by linear regression methods. Additionally, KNN regression can be used with both continuous and categorical predictor variables, making it useful for both numerical and categorical data [40]-[45].

4.1. How The Algorithm Works

KNN regression algorithm is a straightforward machine learning algorithm for predicting continuous variables by finding the K nearest neighbors to a new data point. The flowchart outlines the process starting with inputting the training dataset and the number of nearest neighbors to consider. A new data point is then inputted, and the algorithm computes the distance between the new data point and all data points in the training dataset. The K nearest data points are selected, and their average outcome is used to predict the outcome for the new data point. The Mean Absolute Error (MAE) can be calculated to evaluate the accuracy of the model's prediction by measuring the average absolute difference between the predicted and actual. (The flowchart of this algorithm is shown in Fig. 3)

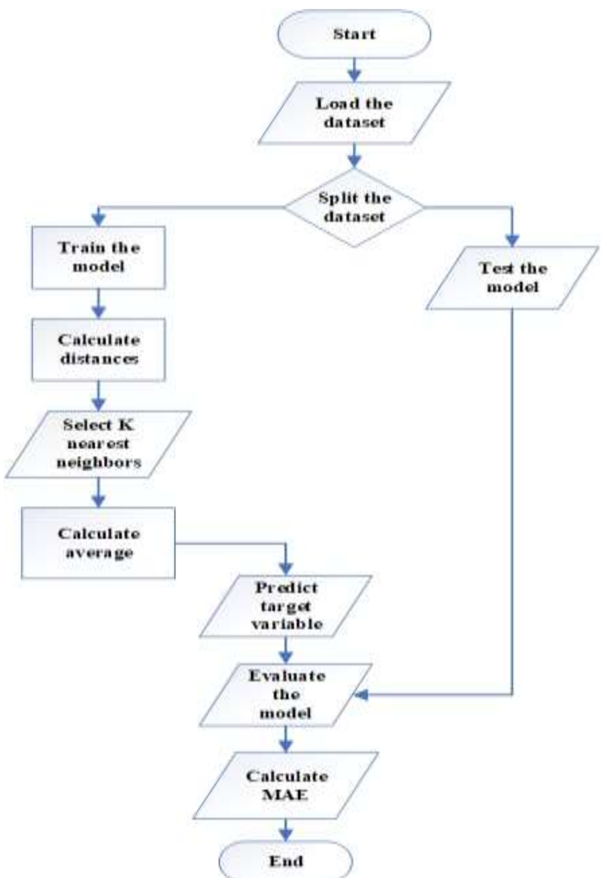

Fig. 3. Flowchart of KNN Algorithm.

4.2. Benefits of Using Machine Learning

Using machine learning algorithms has several features:

- It is a new approach.
- It can produce the exact output value for each x to find the optimal point. In previous methods, only guessing the point was possible, which is not accurate.

- To easily find the optimal point, the outputs can be sorted in ascending or descending order.

4.3. Methodology and Parameters of Machine Learning Model

In this study, we have extracted the data points of the image's graph and converted them into coordinate form, which we have then placed in a CSV file as input for the model. we utilized the following libraries for data analysis and modeling: numpy, pandas, and matplotlib.pyplot. In addition, we employed the KNeighborsRegressor model from the scikit-learn library, which was utilized with its default parameters.

Table 1 contains information about the different parameters and their descriptions for the scikit-learn implementation of K-Nearest Neighbors (KNN) regression which has been presented in the table, and values are relevant to this article.

Table 1. Different parameters and their descriptions for the scikit-learn implementation of KNN regression .

Parameter	Description	Value
n_neighbors	The number of nearest neighbors to consider when making predictions	5
weights	The weight function used in prediction (`uniform` or `distance`)	'uniform'
algorithm	The algorithm used to compute the nearest neighbors (`auto`, `ball_tree`, `kd_tree`, or `brute`)	'auto'
leaf_size	The size of the leaf nodes in the tree-based algorithms	30
p	The power parameter for the Minkowski distance metric (`1` for Manhattan distance, `2` for Euclidean distance)	2
metric	The distance metric used to calculate the distance between two points	'minkowski'
metric_params	Additional keyword arguments for the chosen distance metric	None
n_jobs	The number of CPU cores to use for parallelizing the computation of the nearest neighbors	None

The train_test_split function was used from the scikit-learn library for splitting the dataset into training and testing subsets. Finally, the mean_absolute_error function from the scikit-learn metrics module was used to evaluate the performance of the KNeighbors Regressor model.

4.4. Mean Absolute Error

Mean Absolute Error (MAE) is a statistical metric used to measure the average difference between actual and predicted values in a dataset. It is commonly used in regression analysis to evaluate the accuracy of a model's predictions. MAE is a simple and intuitive metric that measures the absolute difference between the predicted and actual values.

If $\hat{y}_i$ is the predicted value of the i-th sample, and y_i is the corresponding true value, then the mean absolute error (MAE) estimated over n_{samples} is defined as:

$$MAE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n} \quad (1)$$

Where, n is the total number of observations. The expression $(Y_i - \hat{Y}_i)^2$ is the quantified difference between the predicted and observed values for the $\mathbf{i^{th}}$ observation. A lower MAE value indicates better predictive accuracy, while a higher MAE value indicates poorer accuracy.

5. RESULTS AND OUTPUTS OF THE MODEL

Fig. 4 shows the results of the proposed model.

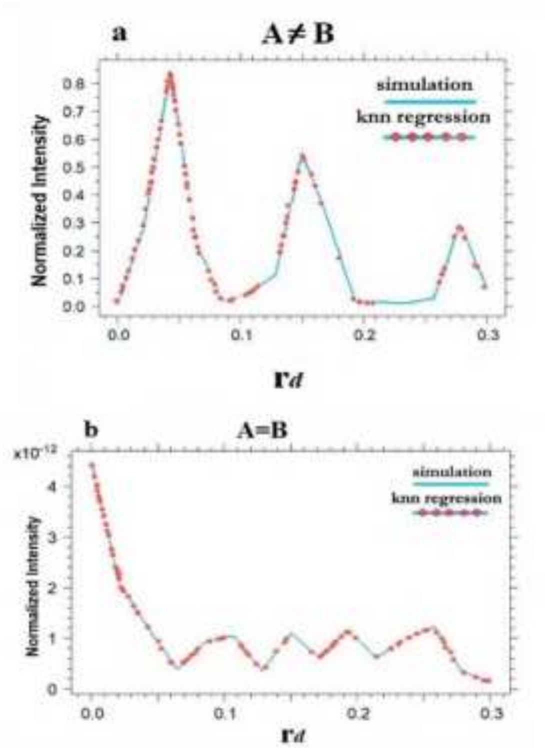

Fig. 4. Comparison of simulation output and model output.

In Fig. 4, the dashed blue line represents the output of the simulation software, and the red dots represent the output of a machine learning algorithm called KNN regression, as shown in the image above. These two cases match perfectly, and as a result, the algorithm has predicted the graph points accurately. The importance of this issue is that when the points are predicted correctly, the optimal point can be easily found. The model's amount of error, according to the MAE criterion, is about 0.004.

In cases where A≠B, the maximum output value should be obtained, and in the case of A=B, the minimum output value of y should be obtained. In other words, in this algorithm, we need to find a point in x that simultaneously has the minimum y in A≠B and the maximum y in A=B. With A=0 and B=1 input, the optimal point at r_d=0.042 in the A≠B case, and its output is 0.882. In another case where A=B (A=0, B=0 or A=1, B=1), the output is multiplied by 10^{-12}, resulting in a minimal number. This value is relatively small and can be ignored. However, it can be said that the output of the mentioned optimal point (r_d =0.042) in the A=B state is equal to 1.202×10^{-12}.

The contrast ratio can be obtained as follows in the value of r_d resulting from the optimization:

$$CR = 10\log\left(\frac{P_{1,min}}{P_{0,max}}\right) = 118dB \quad (2)$$

As can be seen, the proposed structure after optimization has a high contrast ratio.

6. ABBREVIATIONS

MAE: Mean Absolute Error

KNN: K-Nearest Neighbors

XOR: Exclusive OR

PBG: Photonic Band Gap

Si: Silicon

7. CONCLUSION

In this paper, a novel method for designing and optimizing an all-optical XOR gate using machine learning has been proposed. The K-Nearest Neighbors (KNN) algorithm, which is a non-parametric machine learning algorithm used for regression tasks, has been employed for the proposed method. Nonlinear relationships between the predictor and response variables can be captured by the KNN algorithm, making it a versatile method that can be applied to a wide range of problems. The design of an all-optical XOR gate using a two-dimensional photonic crystal structure was carried out by applying the proposed method. It was observed that an all-optical XOR gate with high output power in logic 1 and very low power in the logic 0 state could be designed using the proposed method. The proposed method is considered a promising approach for the design and optimization of all-optical logic gates. In the future, the proposed method is planned to be extended to the design of other all-optical logic gates, such as AND, OR, and NOT gates. The use of other machine learning algorithms for the design and optimization of all-optical logic gates will also be investigated.

Data Availability. Data underlying the results presented in this paper are available from the corresponding author upon reasonable request.

Funding. There is no funding for this work.

Conflicts of interest. The authors declare no conflict of interest.

Ethics. The authors declare that the present research work has fulfilled all relevant ethical guidelines required by COPE.

REFERENCES

[1] S. Roshani, M.B. Jamshidi, F. Mohebi, S. Roshani, **"Design and Modeling of a Compact Power Divider with Squared Resonators Using Artificial Intelligence. Wireless Personal Communications,"** 117(3), 2085 2020.

[2] A. Lalbakhsh, M.U. Afzal, T. Hayat, K.P. Esselle, K. Manda, **"All-metal wideband metasurface for near-field transformation of medium-to-high gain electromagnetic sources,"** Scientific Reports, 11(1), 1 2021.

[3] A. Pirasteh, S. Roshani and S. Roshani, **"A modified class-F power amplifier with miniaturized harmonic control circuit,"** AEU-International Journal of Electronics and Communications, 97, 202-209, 2018.

[4] A. Lalbakhsh, G. Mohamadpour, S. Roshani, M. Ami, S. Roshani, A.S.M.D. Sayem, M. Alibakhshikenari, S. Koziel, **"Design of a Compact Planar Transmission Line for Miniaturized Rat-Race Coupler With Harmonics Suppression,"** IEEE Access, 9, 129207 2021.

[5] S. Roshani, S. Roshani, **"Design of a high-efficiency class-F power amplifier with large signal and small signal measurements."** Measurement. 149, 106991 2020.

[6] S. Lotfi, S. Roshani, S. Roshani, M.S. Gilan, **"Wilkinson power divider with band-pass filtering response and harmonics suppression using open and short stubs."** Frequenz., 74(5-6), 169 2020.

[7] A. Lalbakhsh, R.B.V.B. Simorangkir, N. Bayat-Makou, A.A. Kishk, K.P. Esselle, **"Advancements and artificial intelligence approaches in antennas for environmental sensing, Artificial Intelligence and Data Science in Environmental Sensing,"** ISBN 9780323905084, 19 2022.

[8] G.S. Paul, K. Mandal, A. Lalbakhsh, "**Single-layer ultra-wide stop-band frequency selective surface using interconnected square rings,"** AEU-International Journal of Electronics and Communication, 132, 153630 2021.

[9] S. Adibi, M. Amin Honarvar, and Ali Lalbakhsh, "**Gain Enhancement of Wideband Circularly Polarized UWB Antenna using FSS, Radio Science,"** 56, 1 2021.

[10] M. Hadei, G. Dadashzadeh, Y. Torabi, A. Lalbakhsh, "**Terahertz beamforming network with a nonuniform contour,"** Applied Optics 61 (4), 1087-1096, 2022

[11] S. Roshani, J. Azizian,S. Roshani, M. Jamshidi, F. Parandin, "**Design of a miniaturized branch line microstrip coupler with a simple structure using artificial neural network,"** Frequenz, 76(5-6), 255-263, 2022.

[12] S. Roshani, and S. Roshani, **"Design of a very compact and sharp bandpass diplexer with bended lines for GSM and LTE applications,"** AEU-International Journal of Electronics and Communications, 1;99, 354-360, 2019.

[13] F. Parandin, A. Sheykhian, "**Design and simulation of a 2 × 1 All-Optical multiplexer based on photonic crystals,"** Optics & Laser Technology, 151, 108021, 2022.

[14] A. Askarian, G. Akbarizadeh, M. Fartash, "**An all-optical half subtractor based on kerr effect and photonic crystals."** Optik 207, 164424, 2020.

[15] S. Olyaee, M. Seifouri, A. Mohebzadeh-Bahabady, M. Sardari, "**Realization of all-optical NOT and XOR logic gates based on interference effect with high contrast ratio and ultra-compacted size,**" Opt Quant Electron, 50, 385, 2018.

[16] F. Parandin, A. Sheykhian, "**Designing a Circuit for High-Speed Optical Logic Half Subtractor,**" International Journal of Circuits, Systems and Signal Processing, vol. 16, pp. 887-891, 2022.

[17] M.J. Maleki, A. Mir, M. Soroosh, **"Designing an ultra-fast all-optical full-adder based on nonlinear photonic crystal cavities,"** Opt Quant Electron 52, 196, 2020

[18] F. Parandin, A. Sheykhian, "**Design of an all-optical half adder based on photonic crystal ring resonator.**" Opt Quant Electron 54, 443, 2022.

[19] A. Askarian, G. Akbarizadeh, M. Fartash, "**All-optical half-subtractor based on photonic crystals.**" Appl. Opt. 58, 5931–5935, 2019.

[20] F. Parandin, S. Olyaee, R. Kamarian, M. Jomour, **"Design and Simulation of Linear All-Optical Comparator Based on Square-Lattice Photonic Crystals. Photonics,**" 9, 459, 2022.

[21] M.R. Jalali Azizpour,M. Soroosh, N. Dalvand, Y. Seifi-Kavian, **"All-Optical Ultra-Fast Graphene-Photonic Crystal Switch,"** *Crystals*, 9(9):461, 2019.

[22] S. Olyaee, F. Taghipour, "**Design of new square-lattice photonic crystal fibers for optical communication applications,"** Int. J. Physical Sci., 6(18), 4405-4411, 2011.

[23] A. Mohebzadeh-Bahabady, S. Olyaee, "**All-optical NOT and XOR logic gates using photonic crystal nano-resonator and based on an interference effect,"** IET Optoelectronics, 12(4), 191-195, 2018.

[24] F. Parandin, F. Heidari, M. Aslinezhad, et al. "**Design of 2D photonic crystal biosensor to detect blood components.**" Opt Quant Electron 54, 618, 2022

[25] A. Askarian, "**Design and analysis of all optical half subtractor in 2D photonic crystal platform.**" Optik 228, 166126, 2021.

[26] F. Parandin, N. Bagheri, "**Design of a 2 × 1 multiplexer with a ring resonator based on 2D photonic crystals,"** Results in Optics, 11, 100375, 2023.

[27] A. Askarian, F. Parandin, "**A novel proposal for all optical 1-bit comparator based on 2D linear photonic crystal.**" J Comput Electron 22, 288–295, 2023.

[28] A. Askarian, F. Parandin, "**Numerical analysis of all optical 1-bit comparator based on PhC structure for optical integrated circuits.**" Opt Quant Electron 55, 419, 2023.

[29] F. Parandin, "**Ultra-compact and low delay time all optical half adder based on photonic crystals.**" Opt Quant Electron 55, 398, 2023.

[30] Nayyeri Raad, A., Saghaei, H. & Mehrabani, Y.S. **"An optical 2-to-4 decoder based on photonic crystal X-shaped resonators covered by graphene shells."** Opt Quant Electron 55, 452 2023.

[31] M.J. Maleki, M. Soroosh, A. Mir, **"Ultra-fast all-optical 2-to-4 decoder based on a photonic crystal structure,"** Appl. Opt. 59, 5422-5428, 2020.

[32] B. Mohammadi, M. Soroosh, A. Kovsarian, et al. "**Improving the transmission efficiency in eight-channel all optical demultiplexers.**" Photon Netw Commun 38, 115–120, 2019.

[33] F. Parandin, A. Sheykhian, N. Bagheri, "**A novel design for an ultracompact optical majority gate based on a ring resonator on photonic crystal substrate.**" J Comput Electron, 2023.

[34] S. Naghizade, H. Saghaei, "**A novel design of fast and compact all-optical full-adder using nonlinear resonant cavities.**" Opt Quant Electron 53, 262, 2021

[35] F. Haddadan, M. Soroosh, N. Alaei-Sheini, **"Designing an electro-optical encoder based on photonic crystals using the graphene–Al2O3 stacks,"** Appl. Opt. 59, 2179-2185, 2020.

[36] F. Parandin, M. Moayed, F. Heidari, "**All-optical diode for terahertz optical power rectification based on two-dimensional photonic crystals,"** Microelectronics Journal, 136, 105779, 2023.

[37] Mokhtarbaf, A., Mosleh, M., Saghaei, H. et al. "**Design and simulation of all-optical majority gates using fluid infiltration approach in photonic crystal slab.**" Opt Quant Electron 55, 265 2023.

[38] S. Olyaee, F. Taghipour, "**Design of new square-lattice photonic crystal fibers for optical communication applications,"** Int. J. Physical Sci., 6(18), 4405-4411, 2011.

[39] F. Parandin; M. Malmir, "**Low Delay Time All Optical NAND, XNOR and OR Logic Gates Based on 2D Photonic Crystal Structure,"** Journal of Electrical and Computer Engineering Innovations (JECEI), 8, 1, 1-8, 2020.

[40] T. Hastie, R. Tibshirani, J. Friedman, **"The elements of statistical learning: Data mining, inference, and prediction (2nd ed.)."** New York, NY: Springer, 2009.

[41] C.M. Bishop, **"Pattern recognition and machine learning."** New York, NY: Springer. 2006.

[42] T. Hastie, R. Tibshirani, J. Friedman, **The elements of statistical learning: data mining, inference, and prediction.**" Springer Science & Business Media, 2009.

[43] N.S. Altman, **"An introduction to kernel and nearest-neighbor nonparametric regression. The American Statistician,"** 46(3), 175-185, 1992.

[44] T. Cover, P. Hart, **"Nearest neighbor pattern classification."** IEEE transactions on information theory, 13(1), 21-27, 1967.

[45] A. Geron, **"Hands-on machine learning with Scikit-Learn, Keras, and TensorFlow: Concepts, tools, and techniques to build intelligent systems."** O'Reilly Media, Inc, 2019.