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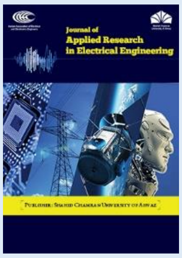

Research Article

Compact All-Optical Encoder Based on Silicon Photonic Crystal Structure

Mohsen Makvandi[1], Mohammad Javad Maleki[2], and Mohammad Soroosh[1,*]

[1] *Department of Electrical Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz 61357-85311, Iran*

[2] *Faculty of Engineering, Lorestan University, Khorramabad 68151-44316, Iran*

* *Corresponding Author:* m.soroosh@scu.ac.ir

Abstract: In this paper, a photonic crystal structure composed of silicon rods is proposed for an all-optical 4*2 encoder. Four input ports are connected to two outputs port via the cross-connections. Different radii of rods as defects are placed in the cross-connection region for coupling the optical waves from the input waveguides to the desired outputs. The total size of the device is about 133 μm^2. Plane-wave expansion and finite difference time domain methods are used to calculate the band diagram and simulation of the optical wave propagation inside the structure, respectively. The maximum rise time of the device for all possible states is just about 205 fs, which is less than one in the previous works. No need for a bias port and using the same power at input ports are other advantages of this work. The normalized output power margins for logic 0 and 1 are calculated by 2% and 34%, respectively. The simulation results demonstrate that the presented structure is capable of using in optical integrated circuits.

Keywords: Encoder, optical devices, photonic band gap, photonic crystal.

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1. INTRODUCTION

An ever-increasing demand for fast processing yields to excessive attention to optical communication processors and systems. High data transferring rate with a possibility for integration are the most dominant issues in designing all-optical circuits [1, 2].

Photonic crystals (PhCs), which are periodic arrays of dielectric, are known as an appropriate medium for designing optical devices because of profitable characteristics, including scalability, the capability of integration, and wide wavelength range [3]. Besides, impressive features such as the photonic band gap (PBG), slow light, and super prism can enhance PhCs-based applications. Recently, researchers aim to design all-optical devices based on PhCs, and many attempts have been made. The various optical devices based on PhCs such as filters [4-6], demultiplexers [7-9], adders [10-12], flip-flops [13, 14], analog-to-digital converters [15-17], decoders [18-20], and encoders [21-28] have been proposed.

For optical circuits, multiple sharing among the waveguides occurs; thus, encoders are potentially required for communication and switching operations. Encoders include logic gates which produce output signals depending on their corresponding powers at input ports. Plenty of PhC-based structures have been proposed and designed for encoding operation. Lee et al. [21] have been presented a 4-to-2 encoder based on the silicon rods with triangle arrangement in the air. This structure was constructed of Y-shaped waveguides and point defects. Although the normalized output power levels for logic 0 and 1 were 5 % and 98%, respectively, the large size of the structure was not applicable for integrated circuits. Another 4-to-2 encoder was proposed by Ouahab and Naoum [22] that consisted of both ring and cavity resonators and L-shape waveguides. They used the polystyrene defects among the silicon rods as nonlinear cavities. The normalized power levels for logic 0 and 1 were 5% and 45%, respectively, and the size of the structure was reduced to 18.5×13 μm^2 in comparison to Ref. [22].

Moniem [23] proposed a PhC-based encoder using the silicon rods with a square arrangement. The encoding operation was based on the NOR logic gate and four ring resonators. Unlike previously discussed researches, a time response analysis was reported. The rise time and the steady-state time of the encoder were about 2 ps and 3.5 ps, respectively. Different optical intensities were used for input and bias waves. Besides, the normalized power levels were not reported. So, the proposed encoder may not be suitable for coupling to other optical devices. Naghizadeh and Khoshsima [24] have presented a 4-to-2 encoder using OR logic gates and ring resonators. They claimed that the encoding operation was correct, but one of the output ports was not active for state 11. The normalized output power levels of logic 0 and 1 were 3% and 45%, respectively. The size of the structure was as large as 723 µm^2, in comparison to other discussed works. Another similar structure was proposed by Mehdizadeh et al. [25], in which the calculated rise time was reduced to less than 1 ps in return for the large size of the structure, which was about 880 µm^2. Moreover, the normalized output power levels of 5% and 27% were reported for logic 0 and 1, respectively.

Gholamnezhad and Zavvari [26] proposed a different structure using GaAs rods with a square arrangement. There were two ring resonators and two bias ports in this structure. The size of the encoder and the rise time were 744 µm^2 and 1 ps, respectively. The normalized output power margins were 1% and 60% for logic 0 and 1, respectively. The radii of rods were reported about 123 nm, which seems to be a challenging issue considering semiconductor fabrication confinements. Another PhC-based encoder has been proposed by Hasangholizadeh-Kashtiban et al. [27] using the elliptical ring resonators and nonlinear rods. The radii of rods and minimum spacing were 106 nm and 100 nm, respectively, which may not be appropriate for semiconductor fabrication technology.

Recently, a 4-to-2 encoder has been proposed by Seif-dargahi [28]. In this structure, four ring resonators were designed, and the size of the device was 792 µm^2. The normalized output power levels for logic 0 and 1 were 5% and 42%, respectively. Although the rise time was almost similar to the previously discussed works, 1.8 ps, the steady-state time obtained for the structure was as long as 6 ps, which reduced the data transfer rate of the encoder. Therefore, the proposed structure may not be applicable for ultra-fast processing systems.

As discussed, some attempts have been made to improve the output characteristics of PhC-based encoders such as rise time, size of the structure, and power margin of output states simultaneously. Besides, considering restrictions imposed by semiconductor fabrication technology, few structures may not be acceptable, even though the operation characteristics were improved. In this study, a new structure is presented using the cross-section waveguides, in which the encoding operation is achieved by altering the radii of defect rods and no optical bias requirement. The size of the structure is decreased to 133 µm^2 in comparison with previous works [21, 22, 24-28]. The rise time is successfully obtained by 205 fs that is less than one in the previous works mentioned earlier [23-26, 28]. Furthermore, the normalized output power margins are 1% and 34% for logic 0 and 1, respectively. By comparing the operating characteristics of all reviewed encoders, it can be stated that the proposed structure can be potentially a proper candidate for being employed as a part of optical integrated circuits.

The paper is organized as follows; in Section 2, the designed encoder is presented, and time and power analysis are investigated in Section 3. Finally, a conclusion of all the above features is presented in Section 4, and the proposed structure is being evaluated.

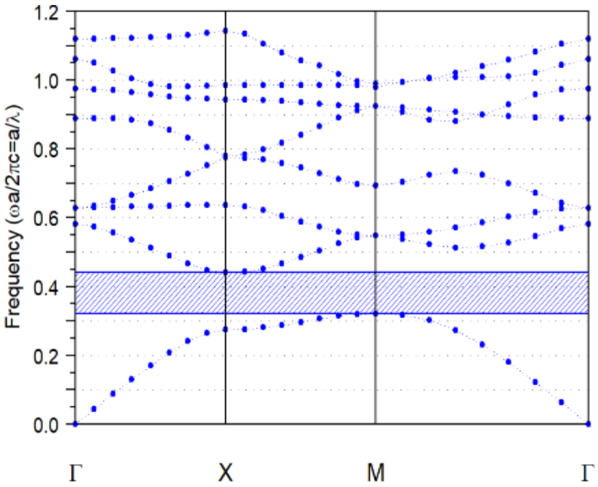


Fig. 1: The band diagram of the fundamental structure.

2. ALL-OPTICAL 4-TO-2 ENCODER

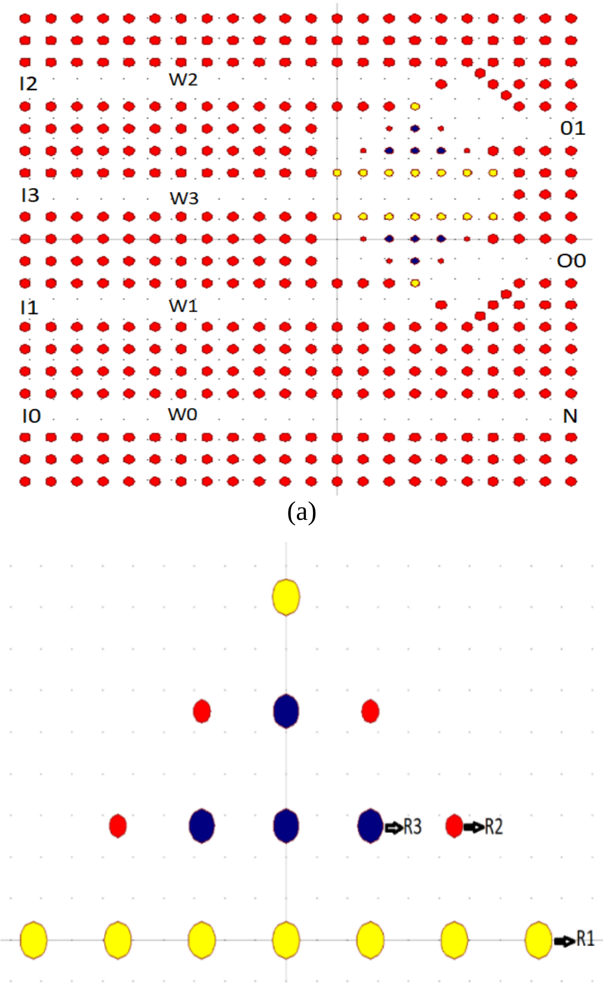
The fundamental structure consists of a two-dimensional 22×22 square lattice of silicon rods in the air at X and Z directions. The refractive index and radii of the rods are 3.46 and r=0.2a, where a is the lattice constant. Considering the period of 550 nm for this arrangement, the structure's size will be about 133 µm^2. The plane wave expansion method is used for the calculation of PBG [29]. In this method, Maxwell's equations are defined as follows:

$$\frac{1}{\varepsilon_r}\nabla\times\nabla\times E=\left(\frac{\omega}{c}\right)^2 E \tag{1}$$

$$\nabla\times\frac{1}{\varepsilon_r}\nabla\times H=\left(\frac{\omega}{c}\right)^2 H \tag{2}$$

where ε_r is the relative permittivity, c is the speed of light in vacuum, and ω is the frequency of optical waves. Using Fourier series expansions for the fields, the eigenvalues $(\omega/c)^2$ were obtained for the different wave vectors. As shown in Fig. 1, the structure has one photonic band gap, $0.33 \leq a/\lambda \leq 0.45$, which is equal to the wavelength range of 1222 nm$\leq\lambda\leq$1667 nm at TM mode. Because the C and L optical transmission bands are covered by this wide range, it is used for this work. So, the optical waves with the mentioned wavelength will not be propagated inside the structure.

The next step is arranging the rods performing as the encoder. Four input waveguides are constructed by removing specific rows of rods, as depicted in Fig. 2a. These waveguides are labeled as W_0 to W_3. The structure is completed by two couplers, consist of three groups of rods. In Fig. 2b, the magnified view of the cross-section is presented. R_1, R_2, and R_3 show the rods' radii and are equal to 0.8r, 0.5r, and 0.75r, respectively, where r is the radius of the fundamental rods. To guide the wave through output ports O_0 and O_1, two defects are placed at the right corners of W1 and W2 waveguides. Port N is placed to exit the optical waves injected from port I0.



(a)

(b)

Fig. 2: (a) The proposed structure for optical encoder (b) the magnified view for the cross-section.

According to Bragg's theory, the incident waves with the wavelength of λ and the reflected waves from the periodic bilayers are in phase if the equation $n_a d_a + n_b d_b = \lambda/2$ is satisfied, where n_a and n_b are the refractive indices and d_a and d_b are the thickness of two layers. Considering the square lattice of the dielectric rods in the air gap, one rod and air gap are assumed as two different layers for the mentioned equation. To obtain the dropping operation at the same wavelength for the cavities, the left side of the mentioned equation should be kept in a constant value. So, changing the radii of the nonlinear rods assists to satisfy the equation. As a result, using the different radii in the structure makes the transmission operation toward the desired outputs.

The working states of the structure have been shown in Table 1. At each time, only one of the inputs is active (at logic1), and other inputs are inactive (at logic 0). In corresponding to the input states, O1 in conjunction with O0 generate the different binary codes. For example, O1=1 and O0=0 will be generated if I2 be equal to 1. When the input ports are not activated, no signal is guided toward the output ports O0 and O1 and results in O0=O1=0. Besides, for the working state I0=1, both output ports O0 and O1 will be also equal to 0. To distinguish two mentioned cases, port N has been placed in the structure. So, N=1 shows the proposed device works at I0=1 state.

Table 1: The working states of the presented structure.

Input States				Output Port		Port N
I3	I2	I1	I0	O1	O0	
0	0	0	1	0	0	1
0	0	1	0	0	1	0
0	1	0	0	1	0	0
1	0	0	0	1	1	0

3. RESULTS

In this research, RSoft Photonics CAD 8.2 has been used for simulation of the proposed structure. To simulate the optical wave propagation throughout the structure, the finite difference time domain method is used. In this method, Maxwell's equations are discretised in space and time domains and components of the electric and magnetic fields are calculated. Also, the perfect matched layer (PML) is supposed to the boundary condition.

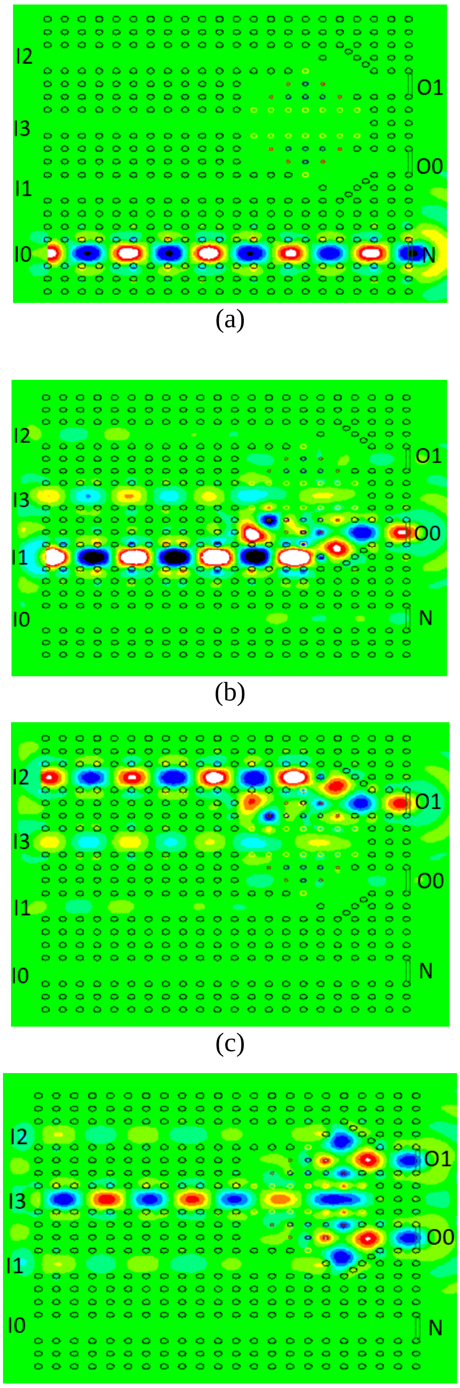
The length of the cells (Δx and Δz) is equal to 0.25 nm which is less than λ/10 [30]. According to the Courant condition, the time step (Δt) should satisfy the following equation [30]:

$$c\Delta t < \frac{1}{\sqrt{\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}\right)}} \tag{3}$$

The time step of 0.029 fs is used for simulation. As shown in Table 1, the optical waves with λ=1550 nm launched at input ports considering the priority of four encoding states and the corresponding field distributions were shown in Fig. 3. Simulation of the structure demonstrates that the incoming optical waves from port I0 guide toward port N, so both O0 and O1 will be at logic 0 (Fig. 3a). As shown in Fig. 3b, the large portion of the launched signal at port I1 was coupled to port O0 and resulted in O0=1. One can see that port O1 will be activated when the optical waves come in port I2 (Fig. 3c). Using the mentioned defect silicon rods in the cross-section region results in the interferences in which the introduced signals from I1 and I2 are guided toward O0 and O1, respectively. Fig. 3d shows that the launched signal from port I3 reach to the cross-section and move toward both ports O0 and O1. In this state, two output ports will be activated.

The correct encoding operation of the proposed structure was shown in Fig. 3, but as discussed previously, the time analysis of the proposed device should be essentially reported. In this work, the time that output power reaches 90% steady-state value is defined as the rise time. The temporal behavior of the proposed encoder is demonstrated in Fig. 4, and the characteristics mentioned above are summarized in Table 2.

For estimating the normalized output power levels of logic states, the worst cases should be considered. So, the minimum power level of all logic states 1 and the maximum power level of all logic states 0 are reported as the encoder's margins. As can be inferred from Table 1, the normalized output power levels for logic 0 and 1 are 2% and 34%,



(a)

(b)

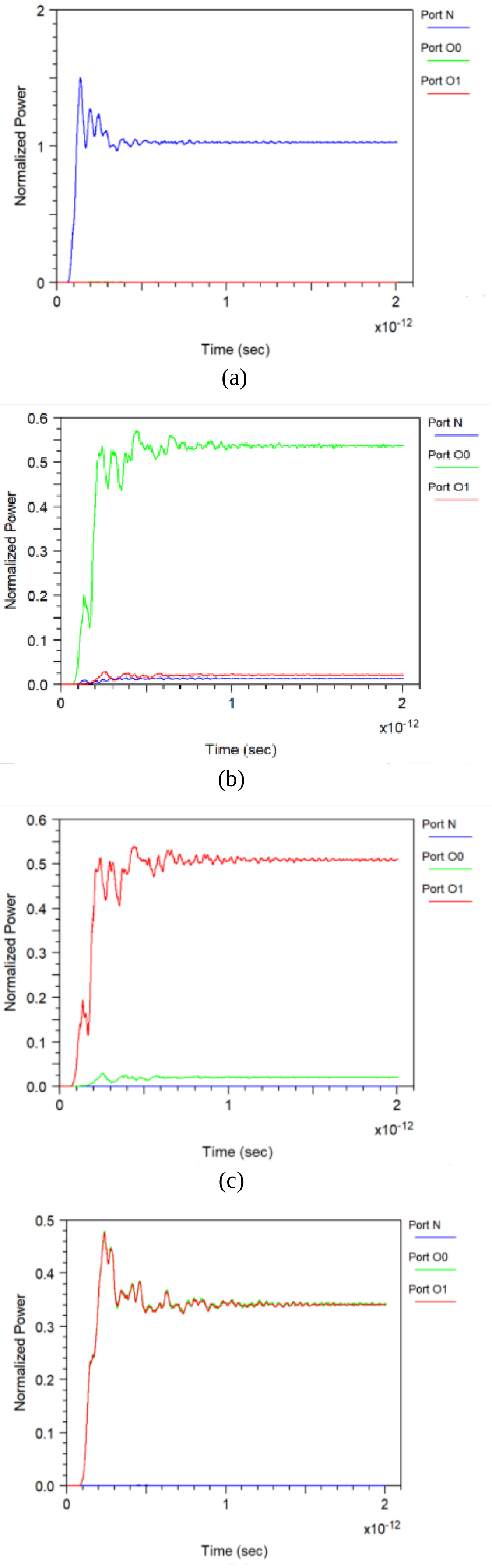
(c)

(d)

Fig. 3: The optical wave propagation throughout the structure for different input states in which only ports (a) I0, (b) I1, (c) I2, and (d) I3 are separately active.

Table 2: The results of time analysis for the proposed device.

Input logic states				Output logic states			Normalized output power (%)			Rise time (fs)
I0	I1	I2	I3	N	O1	O0	N	O1	O0	
0	0	0	0	0	0	0	0	0	0	-
1	0	0	0	1	0	0	100	0	0	115
0	1	0	0	0	0	1	10	2	54	205
0	0	1	0	0	1	0	0	52	2	205
0	0	0	1	0	1	1	0	34	35	190



(a)

(b)

(c)

(d)

Fig. 4: The time response of the encoder when only input ports (a) I0, (b) I1, (c) I2, and (d) I3 are separately active.

Table 3: The main characteristics of the proposed structure in comparison with other works.

Work	Output power margin (%)	Size (μm^2)	Rise time (fs)	Regime
[21]	5-98	-	-	Nonlinear
[22]	5-45	757	-	Nonlinear
[23]	-	1225	2000	Linear
[24]	3-45	723	666	Linear
[25]	5-27	880	1000	Linear
[26]	1-60	744	1000	Nonlinear
[27]	5-40	200	-	Nonlinear
[28]	5-42	792	1800	Linear
This work	2-34	133	205	Linear

respectively. Also, the rise time of the presented structure is 205 fs. As the final assessment, challenging features of the proposed encoder are compared with the previously reported ones, and the results are summarized in Table 3.

One can see that the output power margin is successfully increased, and the rise time and the size of the presented encoder are less than all reviewed ones [22-28]. In addition, there were two bias ports in the design proposed in [23], but in the presented encoder, no bias port will be needed. So, inevitable properties imposed by high optical intensities will be disappeared.

Many attempts have been made for the fabrication of photonic crystal-based structures [31-40]. They have used different methods to fabricate these structures such as colloidal self-assembly, electron beam lithography, and direct writing via multiphoton microlithography. Based on these researches, they have been succeeded in decreasing the radius of rods to 75 nm. The smallest radius of rods in the presented structure is equal to 81 nm. So, one can be optimistic to fabricate the proposed device. Besides, the radii of 30 nm [41, 42], 40 nm [12, 19], 44 nm [43], 45 nm [44], 53 nm [45], 60 [46], and 70 nm [47] have been considered in photonic crystal-based structures for other works. According to the obtained results, the proposed structure is capable of using in optical integrated circuits.

4. CONCLUSION

In this study, a compact photonic crystal-based encoder was presented in which the different radii of rods assisted the optical coupling among the desired waveguides. The total size of the structure was equal to 133μm^2, which was more compact than other works. The rise time of the presented devices was calculated about 205 fs that was smaller than one in all previous works, so it is proper for optical processing applications. Another advantage of the proposed devices is the encoding operation in the linear regime via using the linear rods. This issue makes the possibility of working in low input powers. Also, the input ports work at the same power, and no bias signal is needed. The margins for logic 0 and 1 were obtained 2% and 34%, respectively. As a result, it seems that the presented encoder can be potentially used in optical integrated circuits.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Mohsen Makvandi: Formal analysis, Methodology, Resources, Software. **Mohammad Javad Maleki:** Software, Methodology. **Mohammad Soroosh:** Validation, Visualization, Roles/Writing - original draft, Writing - review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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BIOGRAPHY

Mohsen Makvandi received the B.Sc. and M.Sc. degrees in electronic engineering from Shahid Chamran University of Ahvaz. His fields of interests are all-optical devices based on photonic crystals.

Mohammad Javad Maleki received the B.Sc. and M.Sc. degrees in electronic engineering from Islamic Azad University of Borujerd and Lorestan University, respectively. His fields of interests are all-optical devices based on photonic crystals and plasmonics.

Mohammad Soroosh received the B.Sc. degree from the Isfahan University of Technology at Isfahan in 2000 and the M.Sc. and Ph.D. degrees from Tarbiat Modares University at Tehran in 2003 and 2009, respectively, all in electronics engineering. He joined the Iran Telecommunication Research Center, Tehran in 2003 where he was a researcher at optical communication group. Currently, he is an associate professor of electronics in Shahid Chamran University of Ahvaz, Iran. His research interests are in modeling and simulation of photonic and optoelectronic devices.