

# All Optical Communication Filter Based on Photonic Crystal Structure

Hamed Alipour-Banaei, Farhad Mehdizadeh, and Behnaz Amini

**Abstract**—In this paper we proposed a novel structure for designing all optical filter based on photonic crystal structure. For designing the proposed filter we simply employed a point defect localized between input and output waveguides as wavelength selecting part of the filter. The initial form of this filter is capable of selecting optical waves at  $\lambda = 1554.2$  nm, the transmission efficiency of the filter is 100%. In designing and studying the optical properties of the filter we used plane wave expansion and finite difference time domain methods. After designing the filter we studied the impact of different parameters on the filtering behavior of the structure. The total footprint of the filter is less than  $76 \mu\text{m}^2$ . Simplicity of design and ultra-compact dimensions are the most significant characteristics of our filter.

**Index Terms**—Defect, FDTD, optical filter, photonic crystal.

## I. INTRODUCTION

Currently optical communication networks and optical systems are the best solutions for meeting the ever increasing demand of human kind for fast and high band width communication links, required for sending and receiving the required data throughout the world. For realizing all optical communication networks we require all optical devices such as optical filters, optical demultiplexers and optical switches. One crucial challenge in designing ultra-compact optical devices is the poor confinement of light in small spaces. This challenge has been solved through employing photonic crystals (PhCs) [1]. PhCs have a special frequency (wavelength) range in which the propagation of optical waves inside these artificial structures is forbidden. This special range is called photonic band gap (PBG) [2], [3]. Optical filters play a crucial role in optical communication networks. They used for choosing the desired wavelength and also for separating the very closely spaced optical channels in wavelength division multiplexing (WDM) applications [4]. If we add a defect layer in a 1DPhC we can realize a narrow band transmission filter [5]. In these structures the pass band is located in the PBG region of 1D PhC. by replacing the defect layer by a photonic quantum well [6] we can have a multichannel filter. Another way of realizing multichannel filter based on 1DPhC is replacing dielectric layers by superconducting PhC, in these structures there is no defect layer [7]. Thue-Morse multilayers are other structures proposed for designing optical filters [8]. All of these aforementioned filters are based on 1D PhCs. 1D PhCs do not have complete band gaps so their optical behavior is very

sensitive upon the incident angle of the input light.

Other kind of optical filters are designed based on 2D PhCs. 2D PhCs due to their complete band gaps are not sensitive upon the incident angle of input light. Different mechanisms have been proposed for designing optical filters based on 2DPhCs. One way of realizing optical filter in 2DPhCs is putting a resonant cavity between input and output waveguides [9], [10]. It has been shown that the resonant wavelength of the cavity can be controlled by changing the effective length of the resonant cavity. Using quasi crystal structures are other way of realizing optical filters based on 2DPhCs [11], [12]. The most common mechanism used for designing 2DPhC based filters is ring resonators [13]-[16]. Different kinds of ring resonators have been proposed most recently. In these structures the resonant wavelength depends on the refractive index and dimensions of the resonant ring [17].

In this paper we are going to propose a novel structure for designing all optical filter. In this paper we used a point defect located between input and output waveguides as wavelength selecting mechanism. High transmission efficiency, ultra-compact dimension and simplicity of design are the most significant advantages of our filter. Our results show that by increasing the radius of defect and also the radius of air pores a blue shift will occur in the output wavelengths of the filter, however increasing the refractive index of the dielectric substrate results in a red shift in the output wavelengths of the filter.

## II. THEORETICAL MODELING AND METHODS

The fundamental platform used for designing the proposed filter is a hexagonal lattice of air pores created in a dielectric substrate. The number of air pores in x and y directions are 21 and 15 respectively. The effective refractive index of dielectric material is 2.73. The radius of air pores is 190 nm and the lattice constant of the structure is 530 nm. Before designing the filter we have to calculate the band structure of the fundamental PhC and extract its PBG region. For this purpose we employed Bandsolve simulation tool of Rsoft photonic CAD software, which calculates the band structure of periodic structures based on plane wave expansion (PWE) method [18].

The band structure diagram for this PhC with aforementioned values for refractive index of dielectric material, radius of air pores and lattice constant is shown in Fig. 1. According Fig. 1 this structure has one PBG in TE mode that is shown by dark area in the band structure of the PhC. TE mode is defined as a mode in which light polarization is perpendicular to air pores. There is no PBG for TM mode so all the simulations will be performed in TE

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mode. We observe from Fig. 1 that PBG is in the range of  $0.282 < a/\lambda < 0.395$  or in other words  $1341 \text{ nm} < \lambda < 1879 \text{ nm}$ .

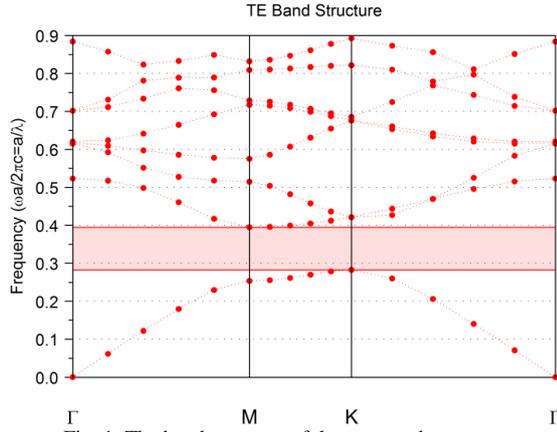


Fig. 1. The band structure of the proposed structure.

Our proposed filter is composed of three main parts: 2 line defects as input waveguide and output waveguide and a point defect located between the waveguides. For creating the point defect, we reduced the radius of one cell between the waveguides, this change in the radius of one cell between the waveguides creates resonant modes between two waveguides, so optical waves at certain wavelengths can be transferred from input waveguide into output waveguide, through the resonant defect. The schematic diagram of the proposed filter is shown in Fig. 2. The point defect is shown with dark blue color, whose radius is  $R=76 \text{ nm}$ .

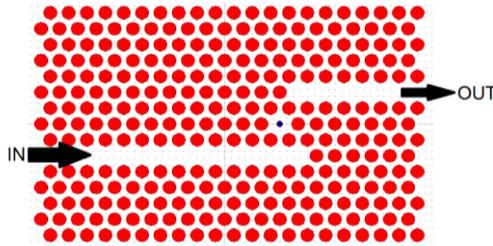


Fig. 2. The final sketch of our proposed filter.

### III. SIMULATION AND RESULTS

After finalizing the design process of the filter we have to investigate the optical behavior of the proposed filter. For this purpose we used Fullwave simulation tool of Rsoft photonic CAD software for testing our proposed structure. Fullwave studies the propagation of light inside PhC based devices based on finite difference time domain (FDTD) method [19]. We used Perfectly Matched Layer (PML) boundary condition for simulating our proposed demultiplexers [20]. We choose the PML width surrounding our structures to be 500 nm. For accurate modeling of the filter we need 3D simulation, but it requires great amount of run time and very powerful computer. So we used effective index approximation method of PhCs for satisfying this requirement and with this approximation we reduce the 3D simulations to 2D simulations [21].

Grid sizes ( $\Delta x$  and  $\Delta y$ ) in FDTD parameters are chosen to be  $a/16$  which equals 33 nm. Due to stability considerations of the simulation the time step  $\Delta t$  should satisfy the ( $\Delta t \leq 1/c\sqrt{(1/\Delta x)^2 + (1/\Delta z)^2}$ ) where  $c$  is the velocity of

light in free space [22]. Following the above-mentioned rule for time step,  $\Delta t=0.021 \text{ ns}$  was chosen. The output spectrum of the filter has been obtained and shown in Fig. 3. Fig. 4 shows that are structure works as an optical filter which only selects the wavelength of 1554.2 nm, the bandwidth ( $\Delta\lambda$ ) is 2.2 nm and the Q-factor ( $Q=\lambda_0/\Delta\lambda$ ) is 706. The transmission efficiency of this filter is 100%. The distribution of optical waves at  $\lambda=1554.2 \text{ nm}$  inside the filter is shown in Fig. 4, as we can see at this wavelength the input waves will couple to the output waveguide through the resonant defect. At the following we are going to investigate the effect of different parameters on the filtering behavior of the proposed filter.

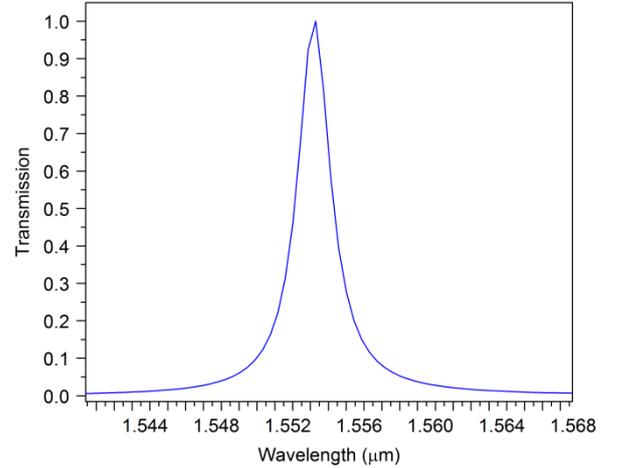


Fig. 3. The output spectrum of our proposed filter.

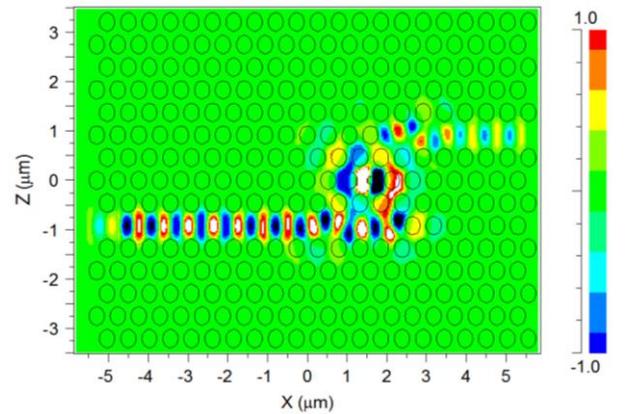


Fig. 4. The distribution of optical waves inside the filter at  $\lambda=1554.2 \text{ nm}$ .

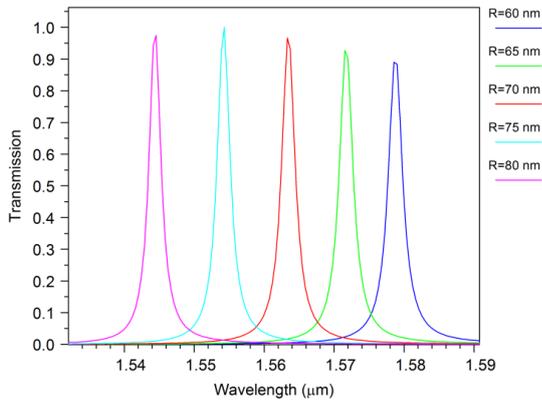
The output spectra of the structure for different values of  $R$  –radius of defect- is shown in Fig. 5. As shown in Fig. 5 by increasing  $R$ , we have a blue shift in output wavelengths, because the resonant wavelengths decrease. Such that for  $R=60, 65, 70, 75,$  and  $80 \text{ nm}$  the output wavelengths are  $\lambda=1579.1 \text{ nm}, 1571.9 \text{ nm}, 1563.7 \text{ nm}, 1554.2 \text{ nm}$  and  $1544.7 \text{ nm}$  respectively.

The detailed specifications of the output wavelengths for different values of  $R$  are listed in Table I.

TABLE I: SIGNIFICANT PARAMETERS OF THE PROPOSED FILTER FOR DIFFERENT VALUES OF  $R$

$R$	$\lambda$ (nm)	$\Delta\lambda$ (nm)	$Q$	$T. E.$ (%)
60	1579.1	2.5	631	90
65	1571.9	2.5	628	93
70	1563.7	2.3	679	97
75	1554.2	2.2	706	100
80	1544.7	2.2	701	98

<sup>a</sup>Transmission Efficiency


 Fig. 5. The output spectra of the proposed filter for different values of  $R$ .

The output spectra of the structure for different values of  $r$  –radius of air pores– is shown in Fig. 6. As shown in Fig. 6 by increasing  $r$ , we have a blue shift in output wavelengths, because the resonant wavelengths decrease. Such that for  $r=188, 189, 190, 191,$  and  $192$  nm the output wavelengths are  $\lambda=1567$  nm,  $1562$  nm,  $1557.6$  nm,  $1553.2$  nm and  $1548.7$  nm respectively.

The detailed specifications of the output wavelengths for different values of  $r$  are listed in Table II.

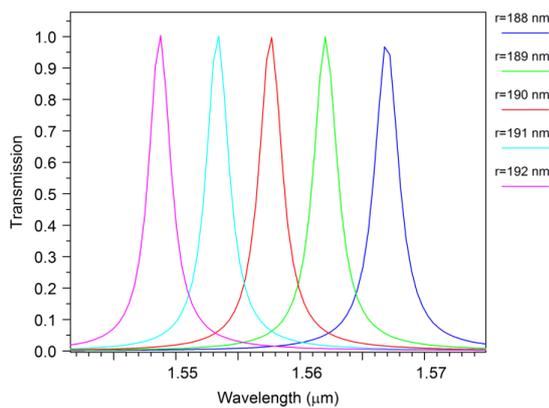

 Fig. 6. The output spectra of the proposed filter for different values of  $r$ .

 TABLE II: SIGNIFICANT PARAMETERS OF THE PROPOSED FILTER FOR DIFFERENT VALUES OF  $R$ 

$r$	$\lambda$ (nm)	$\Delta\lambda$ (nm)	$Q$	$T. E.^*$ (%)
188	1567	2.4	681	96
189	1562	2.3	679	100
190	1557.6	2.2	708	99
191	1553.4	2.2	706	100
192	1548.7	2.2	703	100

\*Transmission Efficiency

Finally, the output spectra of the structure for different values of  $n$  –refractive index of dielectric material– is shown in Fig. 7. As shown in Fig. 7 by increasing  $n$ , we have a red shift in output wavelengths, because the resonant wavelengths increase. Such that for  $n=2.71, 2.72, 2.73, 2.74,$  and  $2.75$  the output wavelengths are  $\lambda=1542.3$  nm,  $1547$  nm,  $1552$  nm,  $1556.6$  nm and  $1561.4$  nm respectively. The detailed specifications of the output wavelengths for different values of  $n$  are listed in Table III.

The red shift and blue shift has been occurred. By increasing the radius of the cells according to Table II, the wavelength shift could be seen from  $1548.7$  nm to  $1567$  nm, also the amount of blue shift and red shift tuned by the size of each defect cells. In addition by changing the refractive indices the wavelengths are shifted.

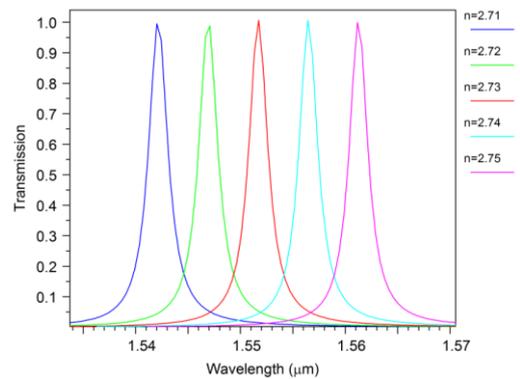

 Fig. 7. The output spectra of the proposed filter for different values of  $n$ .

 TABLE III: SIGNIFICANT PARAMETERS OF THE PROPOSED FILTER FOR DIFFERENT VALUES OF  $N$ 

$n$	$\lambda$ (nm)	$\Delta\lambda$ (nm)	$Q$	$T. E.^*$ (%)
2.71	1542.3	2.1	734	99
2.72	1547	2	773	98
2.73	1552	2	776	100
2.74	1556.6	2.2	707	100
2.75	1561.4	2.3	673	100

\*Transmission Efficiency

#### IV. CONCLUSION

In this paper employing a point defect inside a 2D photonic crystal we proposed an optical filter. Using numerical methods such as PWE and FDTD methods we obtained the optical properties of our proposed structure and investigated the effect of different parameters on the output wavelength of the filter. Our results show that by increasing the radius of defect and also the radius of air pores a blue shift will occur in the output wavelengths of the filter, however increasing the refractive index of the dielectric substrate results in a red shift in the output wavelengths of the filter. The total footprint of the filter is less than  $76 \mu\text{m}^2$ , this shows that our filter is compact enough to be used in all optical integrated circuits. Simplicity of design is the other advantage of our proposed structure.

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