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Design and Simulation of an Optical Channel Drop Filter Based on Two Dimensional Photonic Crystal Single Ring Race Track Resonator

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Abstract

Here, we propose an optical channel drop filter based on single ring two dimensional photonic crystals all circular race track resonator. The structure is made of a square lattice of silicon rods with the refractive index n_1=3.46 which are perforated in air (with refractive index n_2=1). The widest photonic band gap obtains for the filling ratio of r/a = 0.17. Two linear defect W_1 waveguides are instantly coupled to the ring. With the appropriate coupling distance between the ring and waveguide, our channel drop filter is formed. Filter's dropping efficiency for the operational window which is in the C-band of optical telecommunications, is 100% complete for 12-fold resonant mode which is degenerated. Also the quality factor of this mode is 386. Normalized frequencies corresponding to this resonant mode are a/λ = 0.368 and a/λ = 0.362. Full Width Half Maximum bandwidth of the filter at the output transmission spectrum - from 1.535~1.565μm - is 30nm. Our proposed structure is very small and the overall dimension is 12μm×12μm. Resonant modes of the all circular ring resonator and their corresponding degenerate poles are calculated using the PWE method; and the filter's transmission spectrum wavelengths are calculated using 2D-FDTD numerical method.

Keywords: Channel Drop Filter; Photonic Crystal; Race Track Ring Resonator.

INTRODUCTION

Since 1987, photonic crystal (PC) based optical devices have been considered in the design of all optical systems with huge concern mostly due to their compactness, long life period and fast operation speed [1]. Generally, PCs are dielectric or metallo-dielectric periodic structures that have alternate low and high arrangement of dielectric constant materials (refractive index) in one, two or three dimensions [2].

PCS provide a tunable electromagnetic environment to control the interaction between light and matter. They affect the motion of light and prohibit the propagation of electromagnetic waves in all directions within certain frequency ranges known as photonic band gaps (PBGs) [3, 4]. Since the confinement is in a dielectric structure, it can entail very low optical loss. The principal confinement mechanism is Distributed Bragg Reflection (DBR). This differentiates PCs from other types of guiding structures such as optical fibers, micro-spheres, or micro-disks, which rely solely on Total Internal Reflection (TIR) [4, 5].

Optical devices based on PCs, have received many interests in scientific communities for their high capacity, high speed, high performance, long life and compactness which makes them suitable for integration purposes. When a point or line defect is introduced within these structures, their periodicity breaks and the light confines within their PBG. Using this property, several kinds of optical devices can be constructed based on PCs [6, 7].

In recent years many of optical devices have been made based on PCs. i.e. multiplexers [8, 9], de-multiplexers [10], polarization beam splitters [11, 12], add-drop optical filters (ADF) [7, 13-15], channel-drop optical filters [16, 17] and so on. The wavelength selective filter is one of the attractive devices fabricated based on PCs. These types of filters are very important for optical telecommunication systems. Although yet the greatest focus on the PC based wavelength selective filters, has been on the add-drop and channel drop filters [15].

Ring resonators are fascinating elements for wavelength division multiplexing (WDM) and photonics integrated circuits (PICs). Through the confinement of photons, optical ring-resonators enhance the interaction between light and matter. Photonic crystal ring resonators (PCRR) can be considered as a new type of linear defects which their size is determined by the desired resonant wavelength. In comparison with point or linear defect, for reasons such as scalability in size and having many design parameters such as scattering rods radius, distance between the rods and the refractive index of the structure, PCRRs offer better flexibility and adaptability in the structure design [11]. The advantage of PCRRs over conventional integrated optical devices is their functionality and their compactness. These are two important key attributes using PCRRs as novel building blocks for large scale integration [7, 18].

As it is known, within the realm of ring resonators, there are another kind of resonators called race-track resonators (RTR). This work develops a compact integrated optical filter by the mean of photonic crystal race track resonators

(PCRTRs) which has the channel drop (add-drop) capability without altering the signal quality. The novelty of this research consists in the designing of all circular PCRTR to meet WDM filtering needs with high dropping efficiency, high order filtering and high coupling efficiency [9].

Since Dielectric structures can have very low loss and hence very high confinement, quantified by the cavity *Q* value, we will calculate our PCRTR Q factor too to determine its efficiency. Simulation has been done by Finite Difference Time Domain (FDTD) method and the PBG has been calculated by plane wave expansion (PWE) method.

This paper organization is as follow: in the second part of the paper, we discuss the design procedures. We discuss about the simulation results in Section 3 and finally in the last section of the paper we express the conclusions.

STRUCTURE DESIGN

PC Perfect Lattice Design and Optimization

The system under consideration is an array of rods with a two-dimensional square lattice. Since the optical properties and construction technology of optical integrated device based on silicon is well known, and also Si material provides a wide PBG for its large refractive index difference with air, it is selected as the first choice material used in the present paper. The refractive index of silicon rods is n_1=3.46 and the environment is air with refractive index n_2=1. The number of rods in the x-z plane is 21 × 21. Also the desired wavelength performance window is located within C-band of optical telecommunication bands.

To find the best rod's radii for which the PBG is maximum in the TM polarization, we draw the gap map in terms of filling ratio (*r/a*). The best filling ratio that the broadest PBG occurs for it, obtains for *r/a* = 0.17. The normalized frequency range corresponding to this ratio is $0.3076 \leq a/\lambda \leq 0.4526$ and the normalized gap width is $\Delta\omega a/2\pi c \approx 0.145$. For the desired wavelength and the chosen rod's radii by considering the PBG centre as a/λ=0.3801 the lattice constant obtains as *a* = 0.567µm. Also the PBG's corresponding wavelength range is 1.301~1.915µm.

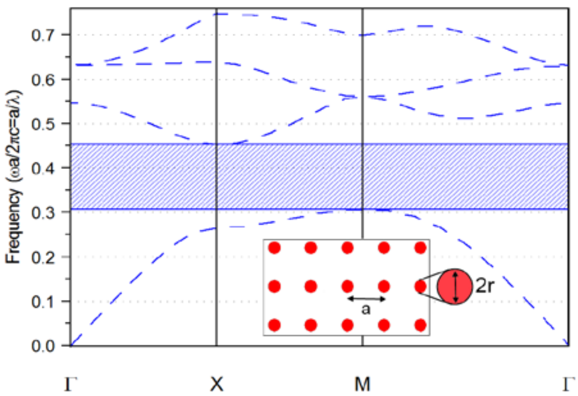

Figure 1. Band diagram of the PC perfect lattice calculated in TM polarization mode by PWE method, this PBG is maxima for filing ratio *r/a*=0.17.

Figure 1 shows the PC's perfect lattice band diagram which is also known as PBG and it is calculated for *r/a*=0.17 using PWE method with TM (electric field parallel to the rod axis) polarization mode. The 'X' axis represents the line connecting points of first Brillion zone (the smallest periodical space in the lattice structure) and 'Z' axis shows the normalized frequency $\omega a/2\pi c = a/\lambda$ where 'ω' is the angular frequency, '*a*' is the lattice constant (distance between centers of two adjacent rods), '*c*' is the light speed in the vacuum and 'λ' is the free space wavelength. The existence of PBG for TM mode in the first 2 bands is clearly visible in this figure.

Linear defect waveguide design

The incident light is coupled into the PCRTR through a W1 waveguide. In Figure 2, the waveguide dispersion curve is drawn for both Perfect lattice and lattice with linear defect (waveguide). For analyzing the waveguides dispersion curves, we used a supercell with the 9*a*×1*a* dimension and the boundary condition with perfect matched absorbing layer (PML). We obtained the W_1 guided mode by collating the dispersion diagrams of the perfect lattice and of the defected-lattice (waveguide), in the space of irreducible Brillion zone for normalized wave numbers. The beginning of the guided mode (red line) is from the normalized frequency a/λ=0.3142 in the $k = \Gamma$ symmetry point.

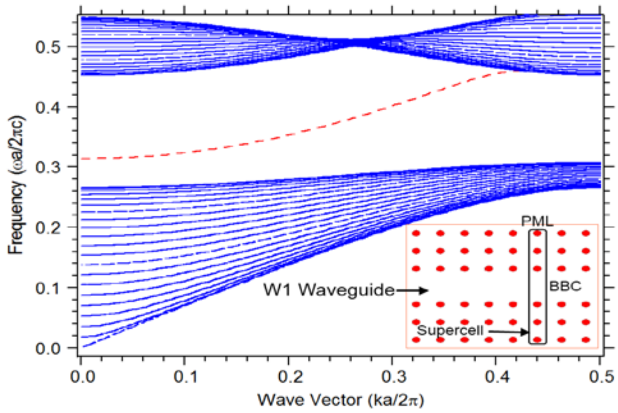

Figure 2. W_1 waveguide dispersion curve, calculated by PWE method for both PC perfect lattice and PC with line defect (waveguide).

PCRTR Design and Optimization

Compared to point or line defects, ring resonators offer scalability in size, adaptability in structure design because of vast design parameters and flexibility in mode design due to their multi-mode nature. Race track resonators can even enhance these. Some of these parameters are radii of scattering rods and the dielectric constant of the structure. The resonator coupled to a line defect waveguide from its side, traps photons at resonant frequency from the waveguide through evanescent coupling modes, and emits almost whole of them in the drop waveguide.

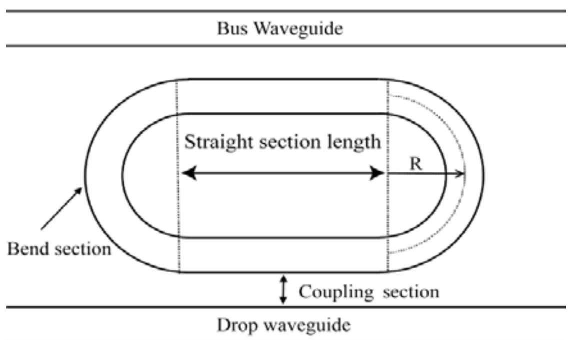

Figure 3. Schematic design of a single ring racetrack resonator. The race track consists of a straight section and the bends.

Using this method, perfect power transfer and complete wavelength selective operation from the bus waveguide to the drop waveguide are obtained in our filter [7, 19]. Figure 3 illustrates the schematic design of a race track resonator. The main difference between a race track and a simple ring resonator is the straight length section which will increase the effective perimeter of the resonator.

Figure 4 shows the PCRTR structure that was created by removing a circular row of rods. The inner rods designed perfectly circular to improve the PCRTR performance. To form the circular shape of our PCRTR outer rods and to optimize its efficiency, we added 12 point-defects to PCRTR structure which were optimized through the FDTD method. Four scattering rods which are indicated with label (S) and are the same as other rods, have been added in the corners of PCRTR and on the centers of the imaginary squares made by their four adjacent rods. These rods act like wavelength reflectors, so they will decrease back reflections in the corresponding corners.

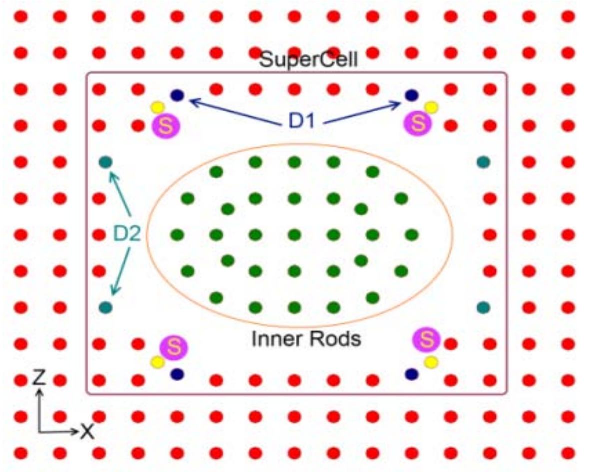

Figure 4. Demonstration of the designed PCRTR and its selected supercell which is used to calculate the resonant modes. D1, D2and S are 12 introduced defects in the PCRTR to improve its performance.

To have a better performance, we moved D1 and D2 defects from their primary places. The D1 defects (with pale blue) along the 'Z' axis are moved to the %4 of their original location and also D2 defect (with strong blue) along the 'X' axis are moved to the %4 of their primary location.

There are many resonant modes for our designed all circular PCRTR and they are easily calculated using the PWE method with the condition of an appropriate supercell size. These resonant modes are multi folded (multi-pole). The single folded mode (mono-pole) often occurs alone, but the others are two degenerate with a phase shift of 180 degree divided by number of poles [16].

The dimensions of these supercell used to calculate the resonant modes is 9*a*×11*a* and the optimum number of bands used to calculate the supercell band structure is 11×(2+9)=121. Its calculations are carried out using PWE method for the electric field component E_y in the TM polarization mode. Figure 5 shows the resonant modes of the proposed all circular PCRR which are located in the ban gap region. These modes are named M1-M5. **Error! Not a valid bookmark self-reference.** contains the calculated quality factors of M1-M5 modes with their centre wavelengths named as λ_0.

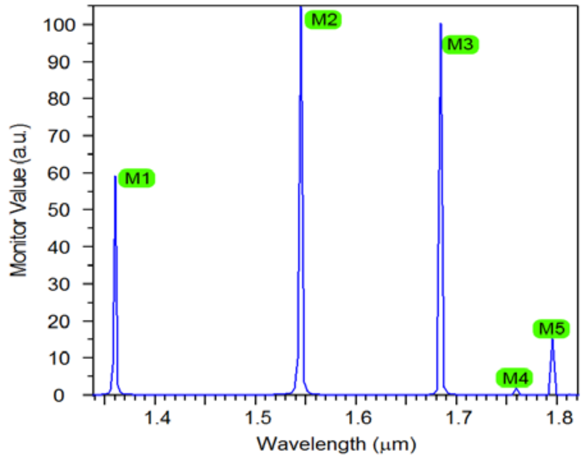

Figure 5. Resonant modes of the race track resonator in the bandgap region calculated using FDTD method. M1-M5 are the PCRTR resonance modes.

Table 1. Calculated quality factor for M1-M5 resonance modes of the PCRTR with their centre wavelengths (λ_0).

Mode	λ_0(μm)	Q
M1	1.360	453
M2	1.55	386
M3	1.684	421
M4	1.759	434
M5	1.796	359

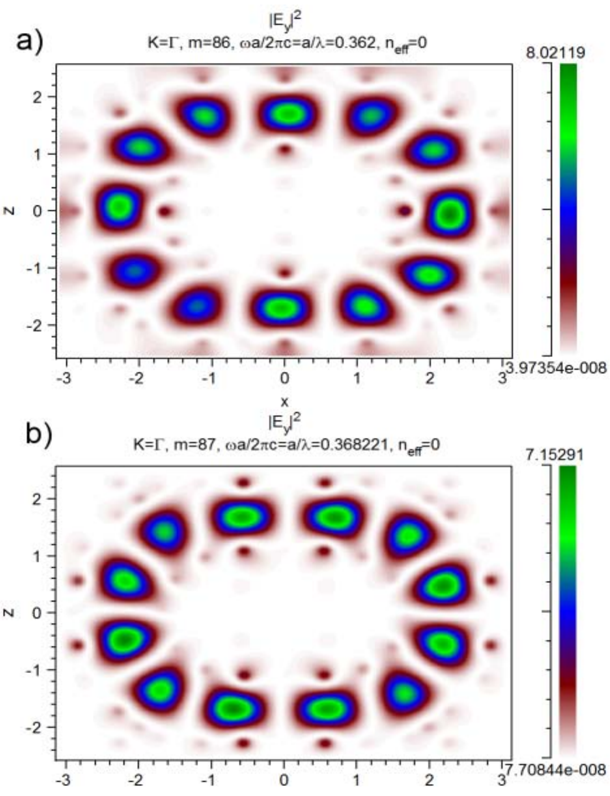

Figure 6. The main resonant modes of the all circular PCRTR with the normalized frequency (a) 0.362 and (b) 0.368.

The main resonant mode of the proposed all circular PCRTR is shown in Figure 6. This mode is a 12 folded one with two degenerate states and there is 18 degree phase shift difference between them. The modes calculated using PWE method for the $|E_y|^2$ field component for the symmetry point of k = Γ in TM polarization mode. The normalized frequencies corresponding to this degenerate pole are a/λ=0.368 and a/λ=0.362 respectively. These frequencies correspond to the wavelengths 0.98µm and 1.55µm. This is obvious that 1.55µm is the desired wavelength.

Channel Drop Filter

Figure 7 shows the final design of our proposed channel drop filter. This filter has one input and three output channels named as B, C and D. The bus waveguide is located between the input and Port A. The other waveguide is the dropping one. The coupling length between the bus waveguide and all circular PCRR, is 5a in the 'X' direction and 1a toward the 'Z' direction. The overall dimension of the structure is about 12µm×12µm which is very small.

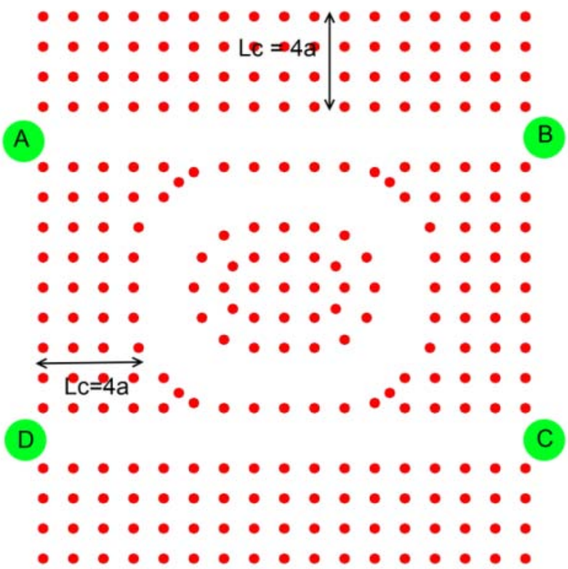

Figure 7. Three dimensional view of the designed filter. The coupling section is L_C=4*a* in the all directions of the PCRTR.

Under Resonance circumstances, the filter's main output is PORT D which performs the dropping job. The filter's desired wavelength performance is the conventional C- band of optical telecommunications.

SIMULATION RESULTS

The filter's transmission features are calculated using the FDTD numerical method with perfectly matched layers (PML) absorbing boundary conditions. A continues wave (CW) Gaussian pulse source used at the input waveguide to excite the fundamental waveguide mode and PCRTRs resonant modes. The FDTD mesh size and time step are Δx=Δy= $a/64$ and Δt= $\Delta x/2c$ (*c* is speed of light in free space).

The filter's power transmission spectrum response is calculated as the relation of transmitted power versus different wavelengths. Figure 8 shows the numerical simulation results for the wavelengths range 1.5~1.6µm. At resonant wavelength, the electric field of the waveguide is completely coupled to the ring and reaches to output, where at off resonance it doesn't couple with the ring and the fields are reflected in the counter direction. The best output peak occurs at 12 folded degenerate modes. The filter's dropping efficiency for the second output channel is 100% at the 1.55µm, which corresponds to the 12 folded degenerate resonant modes. In addition, a Full Width Half Maximum (FWHM) bandwidth of 30nm- from 1.535~1.565µm- is achieved at the output transmission spectrum. The witnessed range of wavelengths and bandwidth almost covers the whole C-Band without affecting neighbouring S and L-band.

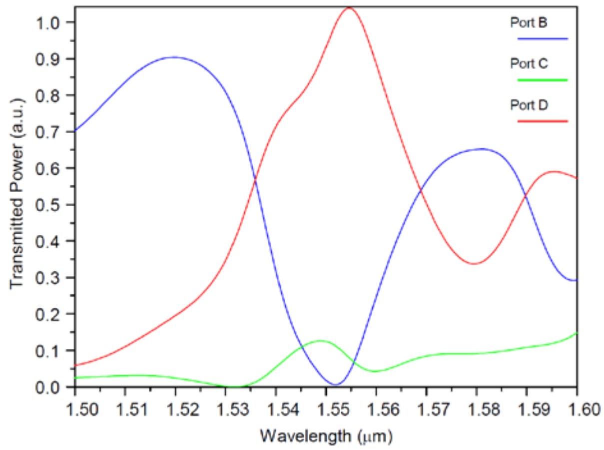

Figure 8. Transmission spectral response of the proposed CDFcalculated using FDTD method. The center wavelenght of this filter is λ=1.55µm.

CONCLUSION

We proposed a channel drop filter based on two-dimensional photonic crystal all circular race track resonators. The structure was made of a square lattice of silicon rods with the refractive index n1=3.46 which were perforated in air (with refractive index n2=1). The widest photonic band gap obtained for the filling ratio of r/a = 0.17. Two linear defect W1 waveguides were instantly clung to the ring. With the appropriate coupling distance between the ring and waveguide, our channel drop filter formed. Filter's dropping efficiency for the operational window which was in the C-band of optical telecommunications, obtained 100% complete for 12 folded degenerated resonant mode. Normalized frequencies corresponding to this degenerate mode were a/λ = 0.368 and a/λ = 0.362. Full Width Half Maximum bandwidth of the filter at the output transmission spectrum - from 1.535~1.565µm - was 30nm. Our proposed structure was very small and the overall dimension was 12µm×12µm. Resonant modes of the all circular ring resonator and their corresponding degenerate poles calculated using the PWE method; and the filter's transmission spectrum wavelengths calculated using 2D-FDTD numerical method.

REFERENCES

[1] J.-M. Lourtioz, Photonic crystals. Towards nanoscale photonic devices (Springer, Berlin, 2005).

[2] K. Busch, Photonic crystals. Advances in design, fabrication and characterization (Wiley, NY, USA, 2004).

[3] J. Joannopoulos, S.G. Johnson, N. Winn, D.M. R., Photonic Crystal: Molding the flow of light (Princeton University Press, New Jersey, 2008).

[4] K. Inoue, K. Ohtaka, Photonic Crystals: Physics, Fabrication and Applications (Springer-Verlog, Berlin Heidelburg, 2004).

[5] M.A. Mansouri-Birjandi, M.K. Moravvej-farshi, A. Rostami, Ultra-fast low threshold all-optical switch implemented by arrays of ring resonators coupled to a Mach-Zehnder interferometer arm: based on 2D- photonic crystals, APPLIED OPTICS 47 (2008) 5041-5050.

[6] M. Djavid, M.S. Abrishamian, Multi – channel drop filters using photonic crystal ring resonators, OPTIK - INT. J. LIGHT ELECTRON OPT. 123 (2012) 167–170.

[7] S. Robinson, R. Nakkeeran, PCRR based add drop filter for ITU-T G.694.2 CWDM systems, OPTIK - INT. J. LIGHT ELECTRON OPT. In Press (2012).

[8] G. Manzacca, D. Paciotti, A. Marchese, M.S. Moreolo, G. Cincotti, 2D photonic crystal cavity-based WDM multiplexer, Photon. Nanostruct. Fundam. Appl. 5 (2007) 164–170.

[9] K.H. Hwang, G.H. Song, Design of a high-Q channel-drop multiplexer based on the two-dimensional photonic-crystal membrane structure, OPT. EXPRESS 13 (2005) 1948–1957.

[10] A. Ghaffari, F. Monifi, M. Djavid, M.S. Abrishamian, Heterostructure wavelength division demultiplexers using photonic crystal ring resonators, OPTIC COMMUNICATIONS 281 (2008) 4028–4032.

[11] V. Zabelin, L.A. Dunbar, N.L. Thomas, R. Houdre, M.V. Kotlyar, L. O'Faolain, T.F. Krauss, Self-collimating photonic crystal polarization beam splitter, Opt. Letters 32 (2007) 530–532.

[12] T. Yu, H. Zhou, J. Yang, X. Jiang, M. Wang, Ultracompact Multiway Beam Splitters Using Multiple Coupled Photonic Crystal Waveguides, J. Phys.D:Appl. Phys. 41 (2008) 1-5.

[13] C.C. Wang, L.W. Chen, Channel drop filters with folded directional couplers in two-dimensional photonic crystals, PHYSICA B. 405 (2010) 1210–1215.

[14] J. Romero-Vivas, D. Chigrin, A. Lavrinenko, C.S. Torres, Resonant add-drop filter based on a photonic quasicrystal, OPT. EXPRESS 13 (2005) 826-835.

[15] Z. Qiang, W. Zhou, R.A. Soref, Optical add-drop filters based on photonic crystal ring resonators, OPT. EXPRESS 15 (2007) 1823-1831.

[16] S. Fan, P.R. Villeneuve, J.D. Joannopoulos, A. Haus, Channel drop filters in photonic crystals, OPT. EXPRESS 3 (1998) 4-11.

[17] Z. Zhang, M. Qiu, Compact in-plane channel drop filter design using a single cavity with two degenerate modes in 2D photonic crystal slabs, OPT. EXPRESS 12 (2005) 2569-2604.

[18] K. Yasumoto, Electromagnetic Theory and Applications for Photonic Crystals (CRC Press, Taylor & Francis Group, USA, 2006).

[19] A. Tavousi, M.A. Mansouri-birjandi, M. saffari, Add-Drop and Channel-Drop Optical Filters Based on Photonic Crystal Ring Resonators, International Journal of Communications and Information Technology (IJCIT) 2 (2012).