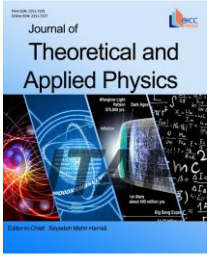

Volume 19, Issue 6, 192557 (1-5)

Journal of Theoretical and Applied Physics
(JTAP)

https://doi.org/10.57647/j.jtap.2025.1906.57

Design and Performance of an All-Optical Four-Channel Filter Based on Linear Photonic Crystals

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Original Research

Received:
7 August 2025

Revised:
4-September 2025

Accepted:
12 October 2025

Publish online:
31 December 2025

Abstract

In this research, we present a novel design for an all-optical four-channel filter based on two-dimensional photonic crystals (2D PCs). This filter is capable of extracting four distinct wavelengths at each output through various techniques such as ring resonators, scattering rods, and resonant microcavities. We employed two well-established numerical methods: the Plane-Wave Expansion (PWE) method for calculating the band gap diagram and the Finite-Difference Time-Domain (FDTD) method to analyze the light behavior within our filter. The results obtained demonstrate that our proposed filter exhibits exceptional performance characteristics, including a remarkably high transmission efficiency of 99.1%, an outstanding quality factor of 15 628, response time is 9 ps, and minimal crosstalk at -41.6 dB. Furthermore, our operating parameters are compared favorably with recent published works, confirming the filter's potential for integration into high-speed WDM optical communication systems.

Keywords: All-optical filter; Integrated optical circuits; Quality factor; Resonant cavity; Ring resonator; Photonic crystal

1. Introduction

In recent years, researchers have tried to use all-optical circuits in several fields due to the development of photonics [1]. Important fields such as computer science, chemistry, medicine, astronomy, pharmacy, and telecommunications, are exploiting photonics to improve the infrastructure that has enabled the development of each field [2]. Enabled applications that have based on Photonic Crystals (PhC) in design and realization such as filters [3]–[11], logic gates [12]–[16], encoders [17], optical fibers based on PhC [18], sensors factor, transmission power, crosstalk, and channel spacing of 387, 77%, -13.5 dB, 4.4 nm, respectively. The four-output all-optical filter was designed by Delphi et al. [35] characterized by quality factor, transmission [19]–[29], demultiplexers [30]–[32]. All-optical add/drop filters are commonly used consisting of a single input channel and three output channels. To evaluate the performance in all types of all- optical filters parameters such as: Quality factor, data rate, channel spacing, and crosstalk are used.

Ghorbanpour and Makouei [33] designed a four-output all-optical filter characterized by quality factor, transmission power, crosstalk, and channel spacing of 5967, 90%, -16.5 dB, 3 nm, respectively. In another work, Alipour-Banaei et al. [34] presented a design of a four-channel all-optical filter characterized by quality

power, crosstalk, and channel spacing of 5443, 93.5%, -14.9 dB, 2.6 nm, respectively.

In this work, we proposed a linear all-optical filter based on photonic crystals which is designed by four channels using resonant cavities coupled with two ring resonators placed in cascade. The characteristics of this proposed design are adequate to have a very high-quality factor, very high bit rate operate, very low crosstalk, and ultra-compact size of this filter.

2. Proposed all-optical fiber

As shown in Fig. 1, the proposed filter is composed of two cascaded ring resonators, including multiple resonant cavities and eight scattering rods positioned at the corners of each resonator. A disconnected square array of 28 × 43 rods has a refractive index of 3.8 (GaAs) suspended in air. The choice of GaAs is advantageous because its high refractive index provides a strong index contrast with air (n air = 1), which is crucial for maximizing the PBG and ensuring excellent light confinement within the filter structure. The area of the fundamental filter structure is equal to 357.86 μm^2. The distance between the two rod centers is assumed to be "a", and the radius of dielectric rods in red is R= 0.2 × a and all rods' radii forming the resonant cavities of each output are shown in Table 1. The filter is designed to operate in the wavelength range from1.5μm to 1.6μm. To analyze the performance of the filter, we employed two standard numerical techniques, the Plane-Wave Expansion (PWE) method and the Finite-Difference Time-Domain (FDTD) method. We first used the PWE method to calculate the band structure of the 2D PC structure. This analysis confirms the existence of a wide PBG for the TE polarization mode, which is the mode analyzed in this study.

The band diagram of the proposed filter, obtained using the PWE (Plane Wave Expansion) method, is shown in Fig. 2, in which appears two photonic bandgaps (PBGs) in TE mode (Transverse Electric): $0.26 < a/\lambda < 0.40$ and $0.69 < a/\lambda < 0.71$. The first PBG covers the third telecommunication window.

The FDTD method was then used to model of light propagation through the device and calculate the transmission spectra. This method solves Maxwell's equations in the time domain. For our calculations, we employed a perfectly matched layer (PML) boundary condition. The spatial mesh size was set to:

$$\Delta x = \Delta z = \frac{a}{20} \tag{1}$$

and the time step was chosen according to the Courant stability criterion:

$$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2} - \frac{1}{\Delta z^2}}} \tag{2}$$

The radii of the rods, particularly those forming the resonant cavities and the coupling sections (referred to as tuning rods), are critical to the filter's performance. The specific radii of the various rods as shown in Table 1 are obtained through an iterative FDTD optimization process. This optimization precisely adjusts the rod dimensions to spectral-shift the resonance frequency for each of the four output channels, thereby maximizing the transmission efficiency and ensuring optimal spectral isolation.

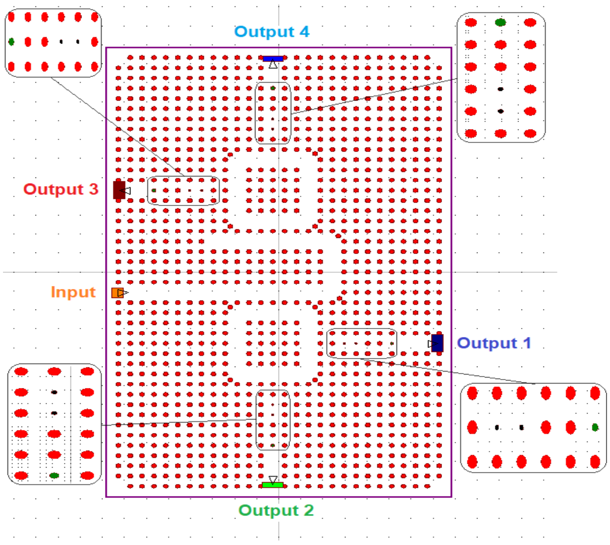

Figure 1: The proposed all-optical filter

Table 1: Rods radii of each channel of the proposed all-optical filter shown by the Fig. 1

Rods	Output1	Output2	Output3	Output4
Black	R*0.409	R*0.42	R*0.44	R*0.46
Red	R	R	R	R
Green	R*0.61	R*0.71	R*0.81	R*0.91

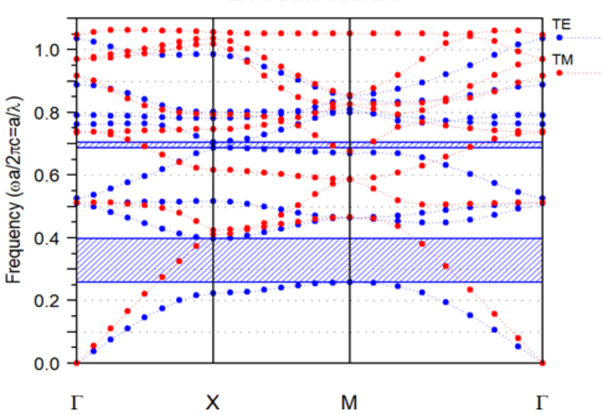

Figure 2. The band diagram for our all-optical filter based on a square lattice

Our system is distinguished from previous works by its highly efficient, cascaded architecture, which enables the simultaneous extraction of four wavelengths in an ultra-compact footprint. This design achieves a significant advancement in key performance metrics, including a Q-factor of 15 628 and crosstalk below −40 dB, which are critical for high-density WDM applications.

3. The numerical results and discussion of the all-optical filter

To calculate the response of our proposed all-optical filter, we excite with an optical Gaussian pulse at the input, as shown in Fig. 3(a). The designed structure allows certain frequencies to pass from the input to the output. An optical signal centered at 1522.6 nm comes out of output 1 of the filter, with a transmission efficiency of 92.06%, a quality factor of 7613, and an optical signal centered at 1539.6 nm comes out of output 2 with a transmission efficiency of 99.1 %, a quality factor of 15 396. The output 3 can guide the optical signal centered at 1562.8 nm with a transmission efficiency of 54.43 %, a quality factor of 15 628, and the output 4 carries the optical signal at 1592.8 nm with a transmission efficiency of 56 % and a quality factor of Q = 7964. The Fig. 3(b) shows the all-optical filter responses in dB to evaluate the crosstalk for the four outputs. The minimum crosstalk measured is −41.6 dB. The crosstalk (CT) is calculated as the ratio of the power leaking into an adjacent channel (P_{leak}) to the power in the desired channel (P_{out}) at the resonance wavelength of P_{out}, expressed in decibels:

$$CT = 10\log_{10}\left(\frac{P_{leak}}{P_{out}}\right) \tag{3}$$

This value of −41.6 dB represents the maximum interference measured across all four channels. We confirm that the crosstalk remains consistently below −40 dB for all channels, confirming the filter's excellent spectral isolation.

The behavior of the optical field inside the filter is illustrated in Fig. 4 and the Table. 2 shows the results obtained, which are better than other recently published works.

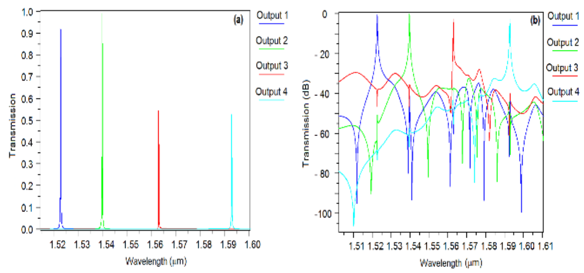

Figure 3. Illustration of the transmission (a) Normalized values, (b) in decibel (dB)

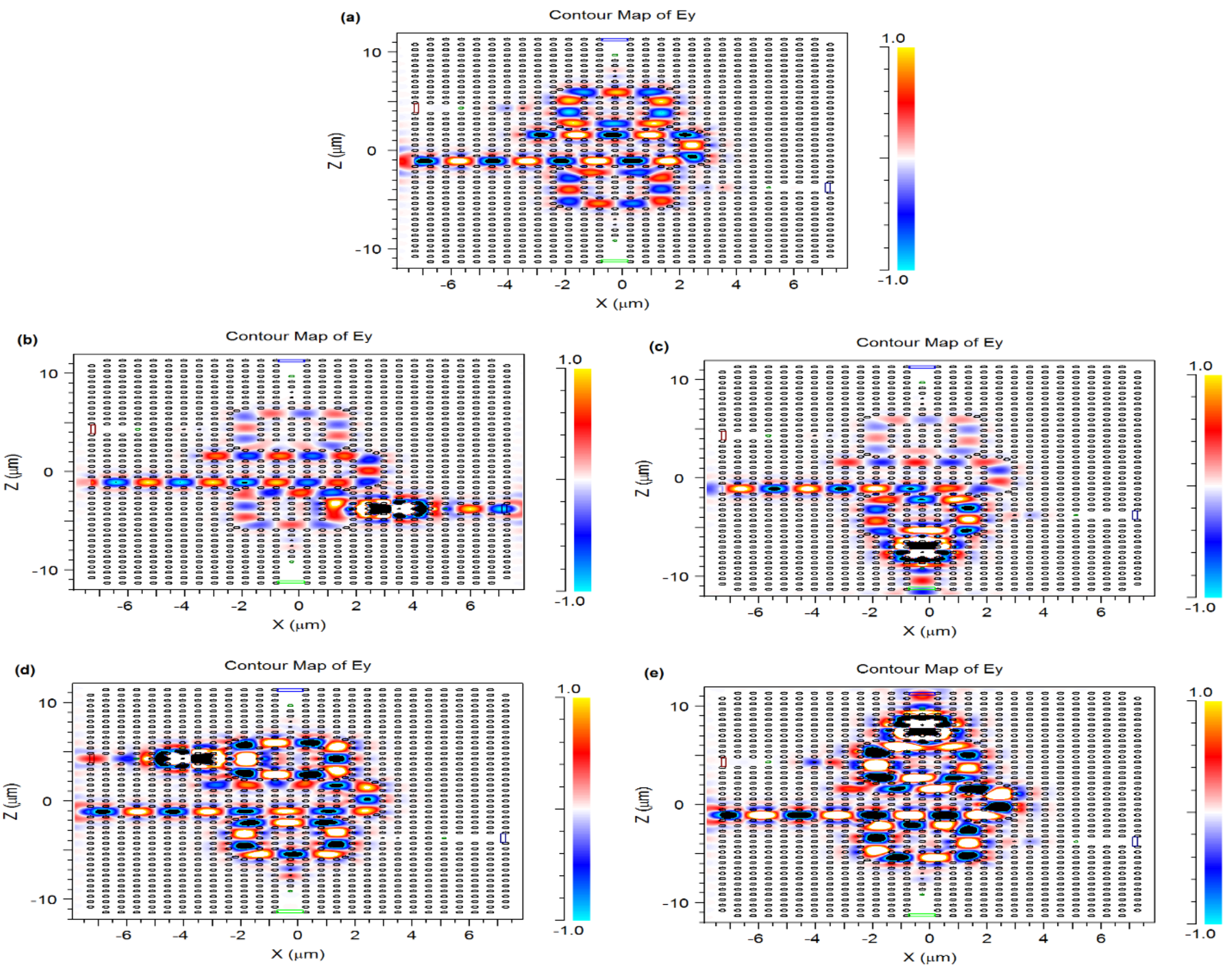

Figure 4. The optical field propagation within the proposed all-optical filter for input optical pulses centered at (a) 1.5190 µm, (b) 1.5226 µm, (c) 1.5396 µm, (d) 1.5628 µm, (e) 1.5928 µm

Table 2. The obtained results compared with previously published works

Previously publishedworks	Number of output channels	Transmission Power (%)	Quality Factor(Q)	Crosstalk in(dB)
Ourwork	4	99.1	15628	-41.6
[35]	2	90	5967	-16.5
[33]	4	98	3805	-41
[35]	2	93.5	5443	-14.19
[36]	2	77.5	387	-13.5

4. Conclusion

In conclusion, we have successfully designed and numerically demonstrated an ultra-compact all-optical four-channel filter based on cascaded Photonic Crystal Ring Resonators (PCRRs). The proposed filter achieves a record-high Q-factor of 15 628, a maximum transmission of 99.1%, response time is 9 ps, and an ultra-low crosstalk of −41.6 dB. The detailed analysis of the cascading effect, polarization, dispersion characteristics, and fabrication complexity confirms the filter's technological robustness and its great potential for integration into next-generation high-density, high-speed integrated optical circuits.

Authors Contribution
All authors conceived of the study, participated in its design and coordination, drafted the manuscript, participated in the sequence alignment, and read and approved the final manuscript.

Availability of data and materials
Not applicable. In fact, all results are obtained without any software and found by manual computations. In other words, the manuscript is in the pure mathematics (mathematical analysis) category.

Conflict of interests
The author states that there is no conflict of interest.

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