Available Online: 14 October 2026 DOI: 10.54254/2977-3903/2026.37783

Optical performance analysis of photonic crystal integrated devices and their potential applications in wavelength division multiplexing systems

Haoqiang Yang

Bishop Allen Academy, Toronto, Canada

yanghq39@gmail.com

Abstract. The rapid development of high-speed and high-capacity optical communication systems creates an increasing demand for compact and high-performance wavelength management devices. Traditional wavelength division multiplexing faces limitations in size, wavelength selectivity, and integration density. Photonic crystal integrated optical devices provide an alternative because their periodic structures can control the propagation, confinement, and filtering of light. This paper investigates the basic operating principles and optical performance of photonic crystal integrated devices and evaluates their potential applications in Wavelength Division Multiplexing (WDM) systems. A literature review and comparative analysis are used to research photonic crystal waveguides, cavities, channel-drop filters, and wavelength-selection devices. The key focus is on transmission efficiency, insertion loss, quality factor, channel spacing, crosstalk, and fabrication tolerance. Recent research indicates that photonic crystal devices can provide compact sizes, high wavelength selectivity, and multifunctional operation on silicon platforms. They can combine with dense WDM, mode division multiplexing, polarization division multiplexing, and inverse-design techniques. Overall, photonic crystal integrated devices illustrate strong potential for future high-density WDM systems, although some challenges including optical coupling, propagation loss, manufacturing costs, and large-scale integrations still need to be solved.

Keywords: photonic crystal, integrated optical device, optical performance, wavelength division multiplexing

1. Introduction

The rapid increase in data traffic imposes high requirements on the capacity, size, and energy efficiency of optical communication systems. Wavelength division multiplexing is an important technique for increasing communication capacity. It transmits multiple optical channels at different wavelengths through the same waveguide or optical fiber. Now, optical systems are moving toward higher channel density and greater integration. Traditional wavelength-selective devices are becoming difficult to make when maintaining a small size and high spectral performance. Therefore, Photonic Crystal (PhC) devices are becoming popular as their characteristics of excellent light field confinement and numerous varying degrees of freedom [1].

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Recent research demonstrates the potential of PhC in practical optical communication applications. Gangwar summarizes recent developments in PhC devices and highlights their ability to control the movement of light and characteristics of strong light confinement and flexible structural parameters [1]. These studies demonstrate strong potential of PhC, but more effort is required to develop and fully use it.

Therefore, this paper focuses on three aspects: the fundamental principles of PhC integrated optical devices, optical performance analysis, and their potential applications in WDM systems. This study mainly uses the literature review method and comparative analysis. It provides references for the design and optimization of PhC integrated optical devices.

2. Principles of photonic crystal integrated optical devices

2.1. Photonic crystal fundamental and basic structures

Photonic crystals are periodic dielectric structures and the refractive index changes spatially in a regular manner. The periodic variation of the refractive index influences the propagation of electromagnetic waves and create frequency regions where certain electromagnetic modes cannot propagate. These regions are known as Photonic Band Gaps (PBG), as shown in Figure 1.

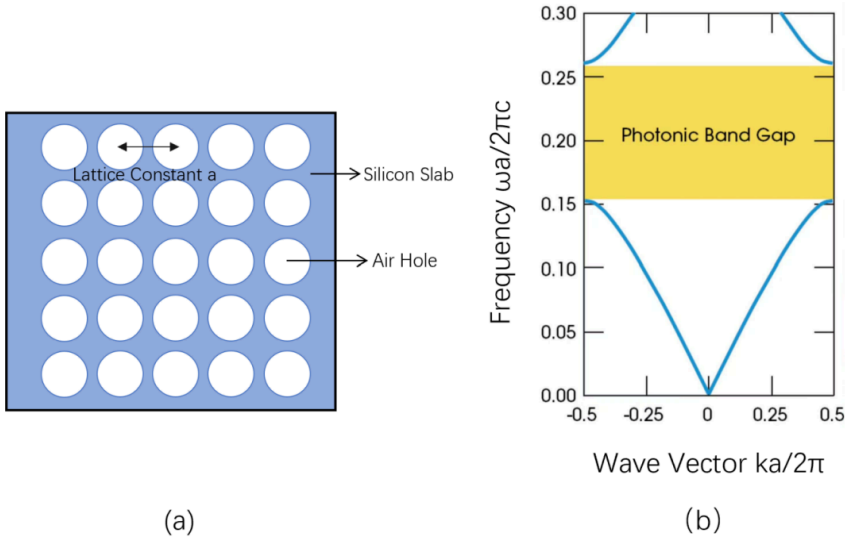


Figure 1. (a-b) Schematic illustration of a two-dimensional photonic crystal and the formation of a photonic band gap

According to recent research, the ability to manipulate the movement and confinement of light through band gap is one of the most important characteristics of photonic crystals [1].

Photonic crystals can be designed as one-dimensional, two-dimensional, or three-dimensional structures. For integrated photonics, two-dimensional photonic crystal slabs on Silicon-on-Insulator (SOI) platforms are particularly attractive because they provide strong optical confinement and CMOS-compatible fabrication.

2.2. Photonic crystal waveguides and cavities

A waveguide can be created by introducing a defect into a periodic photonic crystal. This defect can change the local optical band structure and create a permitted path through which light can propagate. The properties

of this waveguide depend on structural parameters such as the lattice constant, air-hole radius, refractive-index contrast, and defect geometry [1]. This approach possesses significant flexibility as the optical path can be controlled by changing the crystal geometry instead of relying on traditional total internal reflection.

Another important component is the photonic crystal cavity, as shown in Figure 2. By introducing a localized defect, a cavity can be formed to trap light with a particular resonant wavelength. When the incoming wavelength matches the resonant wavelength of the cavity, optical energy becomes strongly localized. This property allows photonic crystal cavities to be used as narrowband filters or channel-drop structures. The cavity can be coupled to a bus waveguide so that the resonant wavelength is transferred to a drop waveguide and other wavelengths remain in the original transmission path [2].

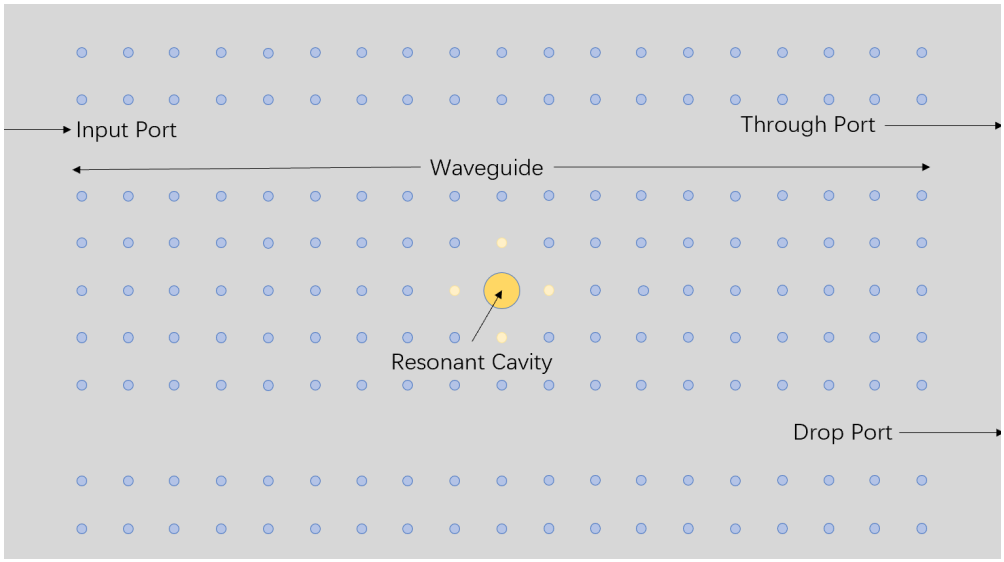


Figure 2. Schematic illustration of a photonic crystal waveguide and cavity-based channel-drop filter

2.3. Applications in WDM and topological photonic crystals

The channel-drop principle is useful for WDM because it contains multiple wavelengths and each wavelength must be separated or routed with limited interference. Multiple cavities with different resonant wavelengths can selectively filter WDM channels. Recent research shows that this concept can be extended to multi-channel devices and even integrated modulation and multiplexing systems [3].

Photonic crystal devices can also use more advanced physical effects. For example, topological photonic crystals can support edge states that are more robust against certain structural perturbations. Tang proposes a topological multichannel add-drop filter based on gyromagnetic photonic crystals, proving that topological characteristics can be incorporated into multichannel filtering architectures [4]. This suggests a potential approach for improving robustness against certain perturbations.

3. Optical performance analysis

3.1. Transmission efficiency, insertion loss, and wavelength selectivity

Transmission efficiency measures how much input optical power reaches the desired output. Insertion loss is related to this property and it represents the optical power lost during transmission through the device.

The performance of PhC channel-drop filters depends strongly on the resonator structure and waveguide-cavity coupling. Zhang illustrates a three-channel channel-drop-filter configuration into which a large-radius dielectric column is introduced [2]. The optimized single-cavity structure achieves a transmission of 99.7% and a quality factor of 12,798.4. For the three-channel device, the average transmission is 94.6%, the average quality factor is 10,617, and the crosstalk is between -30.16 and -50.61 dB [2]. These results show that well-designed resonators have great potential for achieving highly selective wavelength filtering.

Chen proposes a different way of developing a channel-drop filter. This filter is based on an apodized photonic crystal nanobeam grating on SOI [5]. The device achieves a 3-dB bandwidth of 40.1 nm, an Extinction Ratio (ER) of 20 dB, a Sidelobe Suppression Ratio (SLSR) of 19.5 dB, and an insertion loss of less than 1.5 dB [5]. Therefore, different PhC structures can be selected according to different requirements of the WDM system.

3.2. Quality factor, crosstalk, and factors affecting performance

The quality factor, Q, is an important parameter of resonant photonic crystal devices. A higher Q factor generally corresponds to a narrower resonance linewidth and stronger spectral selectivity. Chen designs a four-channel PhC demultiplexer and achieves an optimized resonator Q factor of 9082 and the average Q factor of the complete four-channel device is about 8901. The average channel spacing is 0.77 nm and the average transmission is 88.86% [6]. These figures illustrate that PhC resonators can support closely spaced WDM channels.

Crosstalk is another important performance parameter. In a WDM system, unexpected power from one channel that enters a neighboring channel may cause signal degradation and limit the effective communication capacity. Wu proposes a compact and low-crosstalk coarse wavelength division demultiplexer. The device has six-channels with a 20-nm spacing in the C-band and a compact total footprint of 27 × 12 μm2. The experimental results show a peak insertion loss of 6 dB and the crosstalk is below -20 dB for all output channels [7]. Importantly, the study also reports good simulated fabrication tolerance. It demonstrates how inverse design can help balance compactness and practical robustness.

Another important factor is the interface between a traditional waveguide and a PhC waveguide. A direct connection may lead to the mode mismatch and more optical loss. Chanu and Sonkar investigate a tapered coupling structure and it demonstrates that gradual mode conversion can significantly improve coupling efficiency. The drop efficiency improves from 77% to 91%, and the quality factor and linewidth are 5,042 and 0.31 nm [8]. This observation is particularly essential for practical integrated systems because PhC components need to be connected with other silicon photonic devices.

To provide a clearer comparison of the performance of photonic crystal devices, Table 1 summarizes the key parameters, including transmission efficiency, quality factor, channel spacing, and crosstalk.

Fabrication tolerance should also be considered. PhC devices contain nanoscale structural features, which means that small deviations in hole size, cavity dimension, or lattice spacing can change the resonance wavelength. Therefore, a design that performs well under ideal simulation conditions may show lower performance after fabrication.

Table 1. Performance comparison of photonic crystal devices used in wavelength division multiplexing systems

Reference	Device Type	Transmission Efficiency	*Q* Factor	Channel Spacing	Crosstalk	Advantage
[2]	Three-Channel Channel Drop Filter	99.7% (single channel) 94.6% (three channels)	12,798.4 (single channel) 10,617 (three channels)	N/A	-30.16 to -50.61 dB	Efficient filter capability
[5]	Broadband Nanobeam Filter	<1.5 dB insertion loss	N/A	Broadband operation	N/A	Wide operating bandwidth
[6]	Four-Channel Demultiplexer	88.86%	9,082	0.77 nm	-9.9 to 30.1 dB	High-quality factor
[7]	CWDM (De)Multiplexer	6 dB insertion loss	N/A	20 nm	< 20 dB	Compact footprint and good fabrication tolerance
[8]	Compact Channel Drop Filter	91% drop efficiency	5042	N/A	N/A	High coupling efficiency

4. Potential applications in wavelength division multiplexing

4.1. Multi-channel WDM and demultiplexing

The most direct application of photonic crystal integrated optical devices is WDM filtering and demultiplexing, as shown in Figure 3. In this system, a group of wavelength channels enters the same waveguide, and each wavelength must be separated into its output path. Since PhC cavities can be designed to resonate at specific wavelengths, arrays of cavities or channel-drop filters can be used to complete this task in a compact area.

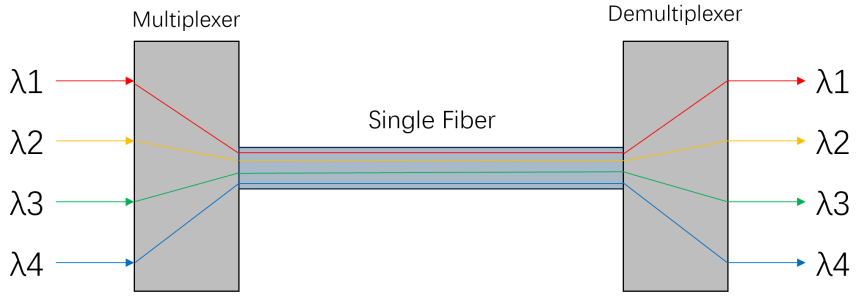


Figure 3. Principle of wavelength division multiplexing and demultiplexing

Hu and Chen propose an eight-channel integrated device. The structure combines eight photonic crystal AAH cavities with eight reflection cavity filters to achieve electro-optic modulation and dense wavelength division multiplexing. They emphasize that the use of PhC waveguides is flexible in device design and channel expansion [3].

Additional studies investigate four-channel demultiplexers and nonlinear photonic crystal resonators, further demonstrating the flexibility of PhC structures for wavelength filtering and optical signal processing [9, 10].

4.2. Hybrid multiplexing and future development

The potential of photonic crystals is not limited to traditional WDM. Combining wavelength division multiplexing with mode or polarization division multiplexing can further increase the capacity of integrated optical systems.

Chanu and Sonkar propose a 12-channel hybrid wavelength-mode division multiplexer based on 2D photonic crystals [8]. The design combines microring resonators for wavelength division multiplexing with asymmetric directional couplers for mode division multiplexing. Their simulations show a maximum channel spacing of 5.05 nm and a maximum insertion loss of 0.97 dB [8]. This demonstrates that PhC-based structures can be integrated into more complex multiplexing architectures rather than being used only as isolated filters.

Recent studies also explore topological photonic crystal structures to improve device robustness and compactness [11, 12]. Inverse design and topology optimization are also important for future PhC WDM systems. Sun applies topology optimization to the design of a wavelength division multiplexer using photonic crystals [13]. Instead of manually selecting geometric parameters, inverse-design methods search for structures that satisfy optical requirements. This approach can be used to optimize channel spacing, insertion loss, crosstalk, device size, and fabrication tolerance.

Despite these developments, several challenges still exist before PhC devices can be widely used in the WDM systems. The first challenge is fabrication tolerance. Small deviations in nanoscale dimensions can change the resonant wavelengths and reduce channel consistency. The second is optical coupling loss between PhC structures and traditional silicon waveguides. The third is that maintaining low crosstalk becomes difficult as the number of channels increases. Finally, many devices are based on simulations. Further practical experiments are needed to demonstrate their reliability and stability.

5. Conclusion

Photonic crystal integrated optical devices provide an advanced platform for controlling light within compact structures. Their operation relies on photonic band gaps, engineered defects, and resonant cavities, enabling compact optical signal manipulation. Recent studies show that such structures can be integrated with silicon photonic platforms and used to construct channel-drop filters, wavelength demultiplexers, and multifunctional optical components.

The literature in this paper indicates that several optical parameters are important for evaluating photonic crystal devices. Transmission efficiency and insertion loss determine how effectively optical power is transferred through the device. The wavelength selectivity and quality factor determine its ability to distinguish closely spaced channels. Crosstalk is important in WDM applications because interference between neighboring channels can decrease signal quality. Recent research demonstrates high transmission, high Q factors, compact footprints, and low crosstalk in several PhC filter and demultiplexer designs.

Photonic crystals have strong potential for future WDM systems because of their compact size, high wavelength selectivity, and compatibility with silicon photonics. However, challenges such as fabrication tolerance, coupling loss, and large-scale integration still need further investigation.

References

[1] Gangwar, R. K., Pathak, A. K., & Kumar, S. (2023). Recent progress in photonic crystal devices and their applications: A review. *Photonics, 10*(11), 1199.

[2] Zhang, A., Yang, X., & Wang, J. (2024). Design of channel drop filters based on photonic crystal with a dielectric column with large radius inside ring resonator. *Photonics, 11*(6), 554.

[3] Hu, Y., & Chen, H. (2024). Eight-channel integrated device for electro-optic modulation and dense wavelength division multiplexing based on photonic crystals. *Optics Communications, 559*, 130407.

[4] Tang, G., Huang, Y., Chen, J., Li, Z.-Y., & Liang, W. (2023). A topological multichannel add-drop filter based on gyromagnetic photonic crystals. *Nanomaterials, 13*(11), 1711.

[5] Chen, Y., Zhao, Y., Nie, J., Shi, Y., & Chen, X. (2025). Silicon broad-band channel-drop filter based on an apodized photonic crystal nanobeam grating. *Optics Letters, 50*(16), 5137–5140.

[6] Chen, G., Yao, J., Zhu, H., Zhi, T., Wang, J., Xue, J., Chen, L., Tao, T., & Tao, Z. (2025). Design of a four-channel demultiplexer based on photonic crystals with an ultra-high quality factor. *Applied Optics, 64*(10), 2581–2585.

[7] Wu, R., Ding, F., Li, F., & Liu, Y. (2024). Inverse-designed low-crosstalk CWDM (de)multiplexer assisted by photonic crystals. *Journal of Lightwave Technology, 42*(14), 4899–4905.

[8] Chanu, S. A., & Sonkar, R. K. (2023). High coupling efficiency photonic crystal waveguide for compact channel drop filter design on silicon-on-insulator platform. *Optical Engineering, 62*(8), 087101.

[9] Boudissa, A. (2025). Design and analysis of a 2D photonic crystal-based WDM demultiplexer using cavity and quasi-waveguide bend coupling. *Engineering, Technology & Applied Science Research, 15*(4), 25872–25877.

[10] Rafiee, E., & Abolghasemi, F. (2024). An all-optical 1×2 de-multiplexer based on two-dimensional nonlinear photonic crystal ring resonators. *Optoelectronics Letters, 20*(1), 23–27.

[11] Guo, G., Wang, H., Wang, Q., Cui, X., Hou, J., & Lei, Z. (2025). Topologically protected power divider and wavelength division multiplexer based on valley photonic crystals. *Optics Express, 33*, 12240–12252.

[12] Lu, B.-Q., Wu, J.-F., & Li, C. (2025). Design of wavelength division multiplexer based on sandwiched topological waveguides in a valley photonic crystal. *Optics Express, 33*(18), 38284–38296.

[13] Sun, H., Zhuang, Y., He, Y., Shen, S., & Li, Y. (2025). Inverse design of a high-performance wavelength division multiplexer using topology-optimized photonic crystals. *Photonics, 12*(12), 1171.