Meghashree B.S., Venkateswara Rao Kolli*, Santhosh Kumar K.B.*, Sushma N., Usha Desai and Sapna B.A.

High-*Q* photonic crystal ring resonator–based ultra-compact 6-channel C-band demultiplexer with low crosstalk

https://doi.org/10.1515/joc-2026-0341
Received July 30, 2026; accepted August 31, 2026;
published online September 28, 2026

Abstract: Ultra-compact and high-performance photonic crystal ring resonator–based demux may achieve low crosstalk, high Q-factor, and effective multichannel operation in the C-band. In this study, we propose a novel 6-channel dense wavelength division demultiplexer based on photonic crystal hexagonal ring resonators is designed and analyzed. To obtain the linearity in the intensity of demux, a novel technique of tuning holes is incorporated. By adjusting the radii of resonator holes and monitor holes – collectively known as special holes, the resonating wavelengths are precisely adjusted. Six asymmetrical hexagonal ring resonators are used in the suggested demux to accomplish effective channel separation. The Finite-Difference Time-Domain Method approach is used to examine the device performance, while the Plane Wave Expansion Method is employed to derive the photonic bandgap structure. For short-haul optical communication systems, the design maintains a channel spacing of 0.8 nm in accordance with ITU-T specifications. The suggested demux achieves crosstalk levels between −17.23 dB and −23.97 dB and a quality factor of 12,875 spanning a wavelength range of 1,544 nm–1,550 nm in the C-band. Compact design and improved selectivity for Dense Wavelength Division Multiplexing applications are achieved by using an asymmetrical hexagonal resonator with optimal hole tuning.

Keywords: photonic crystal; DWDM; finite difference time domain method; demultiplexer; hexagonal ring; C band

***Corresponding authors: Venkateswara Rao Kolli and K.B. Santhosh Kumar**, Department of Electronics and Communication Engineering, Malnad College of Engineering, Hassan 573202, Affiliated to Visvesvaraya Technological University, Belagavi, 590018, Karnataka, India, E-mail: vrk@mcehassan.ac.in (V.R. Kolli), kbs@mcehassan.ac.in (K.B. Santhosh Kumar). https://orcid.org/0000-0003-3168-2449 (V.R. Kolli)

Meghashree B.S. and Sushma N., Department of Electronics and Communication Engineering, Malnad College of Engineering, Hassan 573202, Affiliated to Visvesvaraya Technological University, Belagavi, 590018, Karnataka, India, E-mail: bsm@mcehassan.ac.in (M. B.S.), ns@mcehassan.ac.in (S. N.)

Usha Desai, Department of Electronics and Communication Engineering, S.E.A College of Engineering and Technology, Bengaluru, 560036, Karnataka, India, E-mail: Dr.ushadesai@seaedu.ac.in

Sapna B.A., Department of Electronics and Communication Engineering, PSG Institute of Technology and Applied Research, Coimbatore, 641062, India, E-mail: sapna_psmi@yahoo.co.in. https://orcid.org/0000-0003-4611-5885

1 Introduction

Wavelength Division Multiplexing (WDM) serves as a fundamental architecture in optical communications, enabling the concurrent transmission of multiple independent data streams across a single optical medium by utilizing discrete carrier wavelengths. By multiplexing various optical frequencies onto a single fiber, WDM significantly enhances the aggregate bandwidth and throughput of communication systems, within the domain of modern photonic integrated circuits (PICs) [1], contemporary research is primarily focused on addressing the inherent limitations of these systems, specifically concerning device footprint, insertion loss, and spectral crosstalk, which remain critical barriers to achieving ultra-high-density integration. To get over these obstacles, the industry is moving away from large, legacy components and toward subwavelength and meta-structure designs as we approach 2026 [2]. Similar to how semiconductors regulate electrons, photonic crystals (PCs) offer a fundamental change in how we handle light, from “guiding” it through pipes (waveguides) to “controlling” it through a crystalline lattice [3]. Optical design has successfully transitioned from “macro” components to the “nanoscale” regime with the development of photonic crystal (PC) technology. A new class of thermally resistant and incredibly tiny WDM components has evolved by applying defect-mode engineering to overcome the intrinsic limits of total internal reflection. Photonic crystals (PCs) are versatile because their photonic band gap (PBG) is a tunable environment rather than only a filter [4]. PCs can become active, multidomain sensors and computing components by changing the lattice geometry or adding particular materials to the flaws [5].

The pursuit of compact, high-performance optical communication components has led to significant advancements in PC-based WDM architectures [6, 7]. Researchers have demonstrated various configurations, ranging from multichannel multiplexers to high-Q tunable filters [7, 8]. For instance, a 2D PC cavity-based multiplexer was shown to support 12-channel operation with a narrow bandwidth of 1.16 nm and 10 nm channel spacing, maintaining a transmission efficiency of approximately 74 % [9]. Similarly, ring resonator designs have proven effective; a PC ring resonator add-drop filter utilizing hexagonal rods achieved 100 % efficiency at 1,511 nm with a 16 nm bandwidth, aligning with CWDM standards [10]. The integration of defect engineering has further enhanced the selectivity of these devices. Tunable filters based on PC resonant cavities have reached quality factors (Q-factors) as high as 3,909 through precise defect manipulation [11]. Demultiplexing capabilities have also seen marked improvements: quasi-square resonator designs have achieved high efficiency and low crosstalk in the 1,521–1,524 nm range [12], while hexagonal resonator–based 5-channel DWDM systems have pushed performance further, reporting a Q-factor of 5,150 and crosstalk suppression of −18.31 dB [13]. Recent innovations have also explored multidimensional integration, such as hybrid WDM/MDM devices that combine photonic crystals with silicon rods to increase integration density while maintaining acceptable insertion loss and crosstalk levels [14]. Furthermore, specialized ring resonator–based channel drop filters continue to demonstrate the high efficiency and narrow bandwidth required for modern CWDM applications [15]. Further innovations in the field have introduced specialized architectures such as L3 cavity-based demultiplexers, which offer high Q-factors and minimized crosstalk within highly compact footprints [16]. Complementary designs, including Y-branch PC demultiplexers, have focused on enhancing spectral performance [17], while quasi-waveguide–based structures have demonstrated the potential for exceptional selectivity, achieving Q-factors as high as 7,658.5 [18]. However, despite these significant technological strides, a persistent challenge remains: the realization of an ultra-compact device that simultaneously provides a high Q-factor, low crosstalk, and efficient multichannel operation specifically within the C-band spectrum. A PC DWDM demultiplexer that uses an overlap ring cavity to achieve low linewidth channels and enhanced spectral selectivity is shown in [19]. The suggested architecture is appropriate for dense optical communication systems because it exhibits improved channel isolation and compactness. A four-channel PC-based demultiplexer with an ultra-high quality factor (Q-factor) is shown in [20], allowing for effective wavelength separation and acute resonance characteristics. For precise optical filtering applications, the study focuses on high Q-factor performance and minimal loss. Overall, both studies demonstrate the efficiency of devices based on PC ring resonators for high-performance and compact DWDM demultiplexing.

To address these limitations, this work presents the design and analysis of a six-channel demultiplexer based on a PC hexagonal ring resonator (HRR). By focusing on the optimization of defect-based waveguide structures and the enhancement of photonic bandgap (PBG) confinement, this design aims to transcend current performance benchmarks. The proposed HRR-based device demonstrates superior compact size, high Q-factor, and efficient channel separation with minimal crosstalk, positioning it as a robust solution for next-generation WDM applications in integrated photonic systems.

2 Design and methodology

A two-dimensional PC structure is engineered with line-defect waveguides, and an HRR is incorporated to fulfill the resonance condition, and the steps involved in the design and methodology of PC-HRR DWDM demultiplexer are as illustrated in Figure 1.

The first equation is the master equation for electromagnetic waves in a PC, often referred to as the photonic-crystal eigenvalue equation or the electromagnetic analog of the Schrödinger equation:

$$\nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) = \left(\frac{\Omega}{v} \right)^2 \mathbf{H}(\mathbf{r}) \tag{1}$$

where:

- $\mathbf{H}(\mathbf{r})$ is the magnetic field distribution,
- $\varepsilon(\mathbf{r})$ is the spatially periodic dielectric permittivity,
- Ω is the angular eigenfrequency,
- v is the speed of light in vacuum.

This equation governs the propagation of electromagnetic modes in periodic dielectric structures and is used to determine the photonic band structure. The characteristics of the analyzed electromagnetic (EM) field using the finite-difference time-domain (FDTD) method are normalized with respect to the input power, expressed as

$$T(f) = \frac{1}{2P_{\text{in}}} \int \text{Re}\{\mathbf{S}(f)\} \cdot \text{d}\mathbf{A} \tag{2}$$

where P_{in} is the input power, $\mathbf{S}(f)$ is the Poynting vector, and $\text{d}\mathbf{A}$ represents the differential surface area. It is evident from Equation (2) that spatial variations in the dielectric

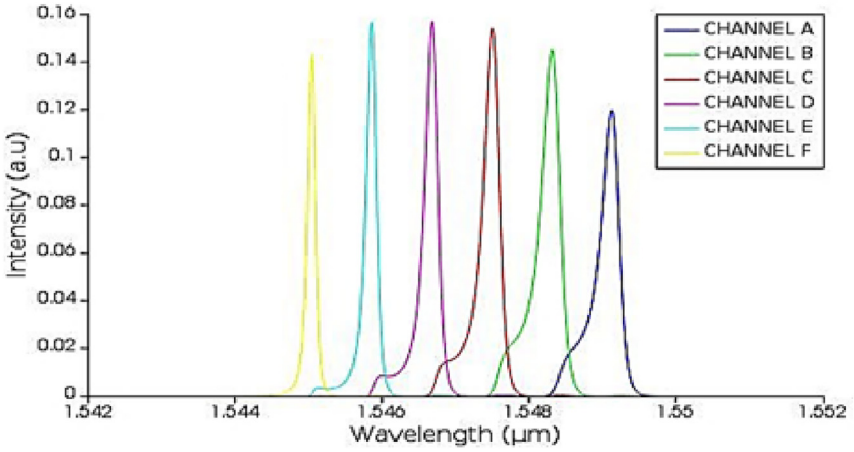


Figure 11: 6-channel demux with varying monitor and resonator holes as given in Table 4 with two reflecting waveguide holes.

Table 5: Performance comparison with selected recent demultiplexers.

References	Structure	Min. channel spacing (nm)	Max. crosstalk (dB)	Q-factor
Sharma et al. [19]	Holes-in-slab	0.8	−15.2	4,200
Zhang et al. [22]	Holes-in-slab	0.4	−18.0	5,200
Gupta et al. [23]	Rods-in-air	0.3	−16.2	6,100
Liu et al. [25]	Holes-in-slab	0.6	−19.3	7,200
Reddy et al. [28]	Holes-in-slab	0.8	−21.5	9,500
Proposed work	Holes-in-slab	0.8	−23.97	12,875

4 Conclusions

This study presents an efficient 6-channel dense wavelength division multiplexing (DWDM) demultiplexer based on a PC hexagonal ring resonator (HRR). The improved arrangement achieves a low interchannel crosstalk between −17.23 and −23.97 dB and a maximum *Q*-factor of 12,875 by adding two reflecting waveguide holes. These findings verify that spectral selectivity and output uniformity are greatly enhanced by exact control over the resonator and monitor hole settings. The suggested design strikes the ideal balance between crosstalk, *Q*-factor, and channel spacing, making it ideal for DWDM applications. All things considered, our work demonstrates the potential of photonic crystals as a reliable foundation for small, high-performing, and energy-efficient optical components, enabling next-generation optical communication systems and sophisticated photonic integrated circuits. The suggested holes-in-slab structure, on the other hand, produces a maximum Q-factor of 12,875, indicating better spectrum selectivity and resonance confinement. Some reported designs have decreased channel spacing; however, they have a lower Q-factor and more crosstalk. The suggested architecture consistently outperforms the majority of previously published designs, achieving a uniform channel spacing of 0.8 nm and a low crosstalk level of −23.97 dB. The revised resonator shape and the addition of two reflecting waveguide holes, which together improve optical field confinement and reduce interchannel coupling, are responsible for these gains. The device is a good option for high-density DWDM integration since it performs well overall in terms of channel spacing, *Q*-factor, and signal isolation. Obtaining the zero cross talk in demuxes needs more challenges. There is fabrication difficulties.

Research ethics: This research does not involve human participants, human biological material, or animals. Therefore, ethical approval from an Institutional Review Board or equivalent ethics committee was not required.
Informed consent: Not applicable, as this study does not involve human participants.
Author contributions: All authors contributed to the conception and design of the study, analysis and interpretation of the results, and preparation and revision of the manuscript. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.
Use of Large Language Models, AI and Machine Learning Tools: None declared.
Conflict of interest: The authors declare that they have no conflicts of interest related to this manuscript.
Research funding: The authors received no external funding for this research.
Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.
Consent for publication: Not applicable.
Originality and submission: The authors confirm that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All

authors have approved the manuscript and consented to its submission to the Journal of Optical Communications.

References

1. Xu Z, Wang J, He Q, Cao L, Su P, Jin G. Optical filter based on contra-directional waveguide coupling in a 2D photonic crystal with square lattice of dielectric rods. Opt Express 2005;13:5608–13.
2. Shen W, Sun X, Zhang Y, Luo Z, Liu X, Gu P. Narrow band filters in both transmission and reflection with metal/dielectric thin films. Opt Commun 2009;282:242–6.
3. Li Voti R. Optimization of perfect absorbers with multilayer structures. Int J Thermophys 2018;39:31.
4. Lee M, Fauchet PM. Two-dimensional silicon photonic crystal based biosensing platform for protein detection. Opt Express 2007;15:4530–5.
5. Kolli VR, Bahaddur I, Prabhakar D, Talabattula S, Talabattulac S. A high Q-factor photonic crystal microring-resonator based pressure sensor. Photon Nanostruct: Fundam Appl 2021;43:100870.
6. Singh BR, Rawal S. Photonic-crystal-based all-optical NOT logic gate. J Opt Soc Am A 2015;32:2260–3.
7. McNab SJ, Moll N, Vlasov YA. Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides. Opt Express 2003; 11:2927–39.
8. Rosenberg A, Carter MW, Casey JA, Kim M, Holm RT, Henry RL, et al. GaN-based photonic crystals and integrated optics. In: Conference on Lasers and Electro-Optics (CLEO). Long Beach, California, United States: Optica Publishing Group; 2006.
9. Manzacca G, Paciotti D, Marchese A, Moreolo MS, Cincotti G. 2D photonic crystal cavity-based WDM multiplexer. Photon Nanostruct: Fundam Appl 2007;5:164–70.
10. Robinson S, Nakkeeran R. Photonic crystal ring resonator based add-drop filter using hexagonal rods for CWDM systems. Optoelectron Lett 2011;7:164–6.
11. Alipour-Banaei H, Mehdizadeh F. Significant role of photonic crystal resonant cavities in WDM and DWDM communication tunable filters. Optik Int J Light Electro Opt 2013;124:2639–44.
12. Kannaiyan V, Savarimuthu R, Dhamodharan SK. Investigation of 2D-photonic crystal resonant cavity based WDM demultiplexer. Opto-Electron Rev 2018;26:108–15.
13. Babu L, Imamvali S, Kumar KS, Kolli VR, Talabattula S, Tupakula S. Design and analysis of photonic crystal hexagonal ring resonator based 5-channel DWDM demux in C band. J Opt 2025;54:2268–74.
14. Nawwar OM, Shalaby HM, Pokharel RK. Photonic crystal-based compact hybrid WDM/MDM (De)multiplexer for SOI platforms. Opt Lett 2018;43:4176–9.
15. Chanu SA, Sonkar RK. Hybrid wavelength–polarization-division demultiplexer based on honeycomb-lattice photonic crystal structures on a silicon platform. Appl Opt 2026;65:4069–77.
16. Talebzadeh R, Soroosh M, Daghooghi T. A 4-channel demultiplexer based on 2D photonic crystal using line defect resonant cavity. IETE J Res 2016;62:866–72.
17. El MO, Labbani A. Analysis of a modified Y-Branch CWDM demultiplexer based on photonic crystal structure. J Microw Optoelectron Electromagn Appl 2024;23:e2024280819.
18. Boudissa A. Design and analysis of a 2D photonic crystal-based WDM demultiplexer using cavity and quasi-waveguide Bend coupling. Eng Technol Appl Sci Res 2025;15:25872–7.
19. Balaji VR, Medha M, Shaik EH, Sivasubramanian A, Ali N, Hegde G, et al. Design and analysis of a photonic crystal DWDM demultiplexer using an overlap ring cavity to drop narrow linewidth channels. Silicon 2026; 18:275–96.
20. Chen G, Yao J, Zhu H, Zhi T, Wang J, Xue J, et al. Design of a four-channel demultiplexer based on photonic crystals with an ultra-high quality factor. Appl Opt 2025;64:2581–5.
21. Chaparala R, Kolli VR, Talabattula S, Tupakula S. Integrated optic microring resonator for various sensing applications: design and analysis. J Opt 2026;55:723–38.
22. Mohammadi G, Orouji A, Danaie M. Narrow-bandwidth optical four-channel demultiplexer based on a compact silicon photonic crystal ring resonator. Photonic Netw Commun 2026;51:9.
23. Xin Y, Wang M, Liu Z, Sun X, Wu Y, Zhang D. Wideband silica mode (de)multiplexer based on an asymmetric multimode interference coupler with phase preset. Appl Opt 2026;65:2680–6.
24. Nivethitha V, Sivasubramanian A. Performance analysis of photonic crystal ring resonator demultiplexer in DWDM system. J Opt 2025;54: 3018–26.
25. Butt MA. Beyond the detection limit: a review of high-Q optical ring resonator sensors. Mater Today Phys 2025;58:101873.
26. Manasvi R, Deepa V, Balaji VR, Soroosh M, Hegde G. Numerical investigation of dual-cavity DWDM optical filters for ultra-narrowband C-Band 6G applications. Silicon 2026;18:897–912.
27. Arruda GS, Morris K, Martins A, Wang Y, Sloan-Dennison S, Graham D, et al. Ultrasensitive Alzheimer's disease biomarker detection with nanopillar photonic crystal biosensors. Optica 2025;12:1587–96.
28. Fu B, Gao R, Yao N, Zhang H, Li C, Lin J, et al. Soliton microcomb generation by cavity polygon modes. Opto-Electron Adv 2024;7: 240061-1.
29. Tarun S, Kumar D, Deepa V, Balaji VR, Hegde G. Design of an L-band DWDM demultiplexer with a review on deep learning in 2D photonic crystals. In: Sixth International Conference on Optical and Wireless Technologies (OWT 2025). Cuncolim, India: SPIE; 2026, 14168:273–82 pp.
30. Steena TB, Ramasamy A. A novel four-channel optical De-multiplexer using photonic crystal ring resonator. International Conference on Microelectronics, Electromagnetics and Telecommunication 2024; 191–202. https://doi.org/10.1007/978-981-97-0644-0_17.
31. Nivethitha V, Sivasubramanian A. Design and simulate the demultiplexer using photonic crystal ring resonator for DWDM system. Opt Quantum Electron 2024. https://doi.org/10.60692/dsk0x-96p57.