

RESEARCH ARTICLE

Design and Analysis of a Low - Crosstalk DWDM Demultiplexer Based on 2D Photonic Crystal Circular Resonant Cavities

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ABSTRACT: The exponential growth in data traffic driven by internet-based services necessitates the development of high-performance optical communication systems. Dense Wavelength Division Multiplexing plays a pivotal role in meeting this demand by enabling the simultaneous transmission of multiple wavelengths over a single optical fiber. This work presents the design and simulation of a two-channel DWDM demultiplexer, engineered using a two-dimensional photonic crystal with a triangular lattice of silicon rods. The device architecture incorporates a bus waveguide, two output waveguides, and specially designed circular resonant cavities that function as wavelength-selective elements. The operational principle is rooted in the photonic band gap effect, where strategically introduced defects within the periodic structure create allowed states for specific frequencies. The plane wave expansion method is employed to analyze the band gap characteristics and optimize the rod radius-to-lattice constant ratio for operation in the optical communication third window. The resonant cavities are meticulously tuned to select desired wavelengths by adjusting the radii of the inner and outer rods, adhering to the ITU-T G.694.1 frequency grid. Finite Difference Time Domain simulations, incorporating perfectly matched layer absorbing boundary conditions, are utilized to evaluate the device's spectral response. The optimized demultiplexer demonstrates resonant peaks at 1529.2 nm and 1531.5 nm, corresponding to a 0.8 nm (100 GHz) channel spacing. The design achieves a high average quality factor of approximately 1698, ensuring excellent wavelength selectivity. A key achievement is the uniform spectral line-width of 0.9 nm across both channels and a low crosstalk level of -22 dB, indicating minimal signal interference between adjacent channels. The average transmission efficiency approaches 89 percent, confirming efficient light coupling from the input bus to the output ports. The compact footprint of 250 μm^2 makes this device highly suitable for integration into large-scale photonic integrated circuits, offering a promising solution for advanced optical networks requiring high data capacity and reliable performance.

Keywords: DWDM Demultiplexer, Photonic Crystal, Circular Resonant Cavity, Crosstalk, Quality Factor, Optical Communication.

Received: 30 September 2025; Revised: 04 November 2025; Accepted: 28 November 2025; Published Online: 12 December 2025

1. INTRODUCTION

The relentless expansion of global internet traffic,

fueled by bandwidth-intensive applications such as high-definition video streaming, cloud computing, and the Internet of Things, has placed unprecedented demands on the underlying optical communication infrastructure. To meet these escalating capacity requirements, network operators and researchers have continually sought innovative methods to maximize the data-carrying potential of existing optical fiber networks. Single mode fiber has emerged as the predominant transmission medium for long-haul and metropolitan area networks due to

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its inherent advantages over traditional coaxial cables, including significantly lower attenuation, minimal signal distortion, and the capacity for high data rate transmission over extended distances without repeater amplification [1–3]. The transmission of information through these fibers is accomplished by modulating laser light at specific wavelengths, each capable of carrying an independent data stream. The technique of wavelength division multiplexing has proven instrumental in harnessing the vast bandwidth potential of single mode fiber by enabling the simultaneous transmission of multiple data channels over a single fiber, each on a distinct optical wavelength. This approach effectively multiplies the network capacity without the need for installing new fiber infrastructure [4, 5]. Wavelength division multiplexing systems are broadly categorized into coarse wavelength division multiplexing and dense wavelength division multiplexing, each governed by distinct International Telecommunication Union standards. Coarse wavelength division multiplexing, as defined by the ITU-T G.694.2 standard, typically supports up to eighteen channels with a relatively wide channel spacing of 20 nm, making it suitable for shorter-distance and cost-sensitive applications where precise wavelength control is less critical [2, 6–9]. In contrast, dense wavelength division multiplexing, standardized under ITU-T G.694.1, offers a far more efficient utilization of the optical spectrum by packing numerous channels with much narrower spacing, typically 0.8 nm corresponding to 100 Gigahertz, 0.4 nm for 50 Gigahertz, or even 0.2 nm for 25 Gigahertz grids [1, 10–13]. This dense packing allows for the support of up to several hundred channels within the low-loss transmission windows of optical fiber, dramatically increasing the aggregate data capacity and making dense wavelength division multiplexing the technology of choice for high-capacity backbone networks that serve the ever-growing population of internet users worldwide [14–18]. At the receiving end of such a dense wavelength division multiplexing system, a crucial component is required to separate the incoming multi-wavelength optical signal into its constituent channels, directing each wavelength to a designated output port for individual detection and processing [17]. This function is performed by an optical demultiplexer. Conventional demultiplexing technologies, such as arrayed waveguide gratings, thin-film filters, and fiber Bragg gratings, have been widely deployed and continue to evolve. However, these technologies often face inherent limitations when scaling to accommodate the ever-increasing number of channels and narrower spacing demanded by next-generation systems. Arrayed waveguide gratings, for instance, can suffer from relatively

large footprints and temperature sensitivity, while thin-film filters may exhibit limitations in achieving the required narrow bandwidth and low loss for ultra-dense grids [19–21]. Furthermore, as photonic integrated circuits emerge as the dominant platform for realizing compact and multifunctional optical components, there is a pressing need for demultiplexer designs that are inherently compatible with planar fabrication processes and offer a small footprint. Photonic crystals have emerged as a powerful platform for manipulating light at the wavelength scale, offering unprecedented opportunities for miniaturization and performance enhancement in optical devices [22]. These structures are artificial dielectric materials characterized by a periodic modulation of the refractive index, with a periodicity on the order of the optical wavelength [3]. The most profound property of photonic crystals is the existence of a photonic band gap, a range of frequencies for which the propagation of electromagnetic waves is strictly forbidden regardless of their polarization or direction of travel, analogous to the electronic band gap in semiconductor materials [4]. This remarkable property arises from the destructive interference of multiple scattered waves within the periodic lattice. To harness the photonic band gap for guiding and manipulating light, it is necessary to introduce defects into the perfect periodic structure. A point defect, created by altering the size, shape, or refractive index of a single rod or hole, or by completely removing it, can confine light to a very small volume, forming a high-quality factor resonant cavity [5]. A line defect, formed by modifying or removing an entire row or column of rods, creates a pathway for light to propagate along the defect, effectively forming a waveguide that can channel light around sharp bends with low loss [23]. The ability to engineer these defects with precision enables the realization of a wide variety of photonic integrated circuit components, including add-drop filters, channel drop filters, beam splitters, and optical sensors, all within a compact footprint [6–9]. The novelty of the work presented in this paper lies in the design and demonstration of a two-channel dense wavelength division multiplexing demultiplexer based on a two-dimensional photonic crystal with a triangular lattice of silicon rods, employing a circular resonant cavity structure with dual-radius tuning for precise wavelength selection. While photonic crystal ring resonators have been explored previously for filtering applications, the specific configuration of a half-resonant cavity with independently adjustable inner and outer ring radii to achieve simultaneous control over resonant wavelength and spectral line-width, while maintaining low crosstalk and high transmission

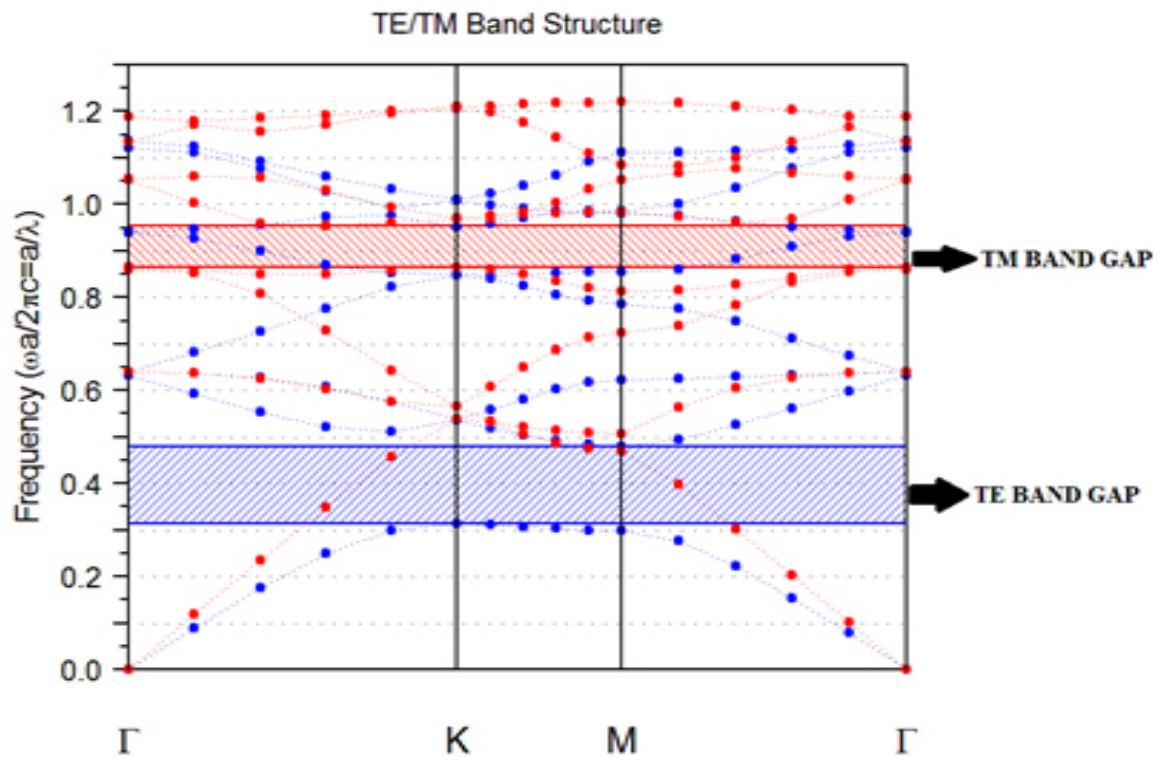


Fig. 1. Photonic band diagram for the 30 by 30 triangular lattice structure before introducing defects, showing the transverse electric and transverse magnetic polarized modes along the high symmetry directions of the Brillouin zone.

efficiency, represents a distinct advancement. This design approach allows for independent optimization of the coupling between the bus waveguide and the cavity, as well as the confinement within the cavity itself, leading to enhanced performance metrics. Furthermore, the proposed structure is engineered to comply with the stringent ITU-T G.694.1 frequency grid, specifically targeting the 100 Gigahertz channel spacing in the 1550 nm communication window, which is essential for practical deployment in existing dense wavelength division multiplexing networks. The combination of a compact device footprint of 250 square micrometers, a high average quality factor of 1698, and a low crosstalk level of -22 decibels positions this design as a promising candidate for high-density photonic integrated circuits. The remainder of this paper is structured to provide a comprehensive account of the design methodology, simulation results, and performance analysis. The following section details the photonic crystal structure and the analysis of its photonic band gap properties using the plane wave expansion method. Section 3 describes the design and operational principle of the single resonant cavity that forms the core of the filtering element. Section 4 presents the complete two-channel demultiplexer architecture, including the bus and output waveguides and the optimized

circular resonant cavities with their specific rod radii for achieving the target dense wavelength division multiplexing channels. Section 5 discusses the results obtained from finite difference time domain simulations, presenting the transmission spectra, quality factor calculations, crosstalk analysis, and the achieved uniform spectral line-width. Finally, the paper concludes with a summary of the key findings and a discussion of the potential impact of this work on the advancement of photonic integrated circuits for high-capacity optical communication systems.

2. EXPERIMENTAL AND THEORETICAL ANALYSIS

2.1 Photonic Crystal Structure and Band Gap Analysis

The proposed dense wavelength division multiplexing demultiplexer is designed using a two-dimensional photonic crystal with a triangular lattice configuration. The triangular lattice geometry is selected specifically because it offers a larger and more isotropic photonic band gap compared to square lattice structures, which proves advantageous for achieving optimal wavelength tuning and efficient

light confinement within a compact footprint. The complete device structure comprises an array of 30 by 30 silicon rods arranged periodically along the X and Z directions, resulting in a total device area of approximately 250 square micrometers. Each individual rod in the pristine lattice possesses a radius R of 96 nm, while the lattice constant a , representing the center-to-center distance between adjacent rods, is set to 690 nm. The silicon material constituting the rods has a relative permittivity of 11.9, corresponding to a refractive index of approximately 3.45 at the operational wavelengths, and the rods are assumed to be surrounded by air with a refractive index of unity.

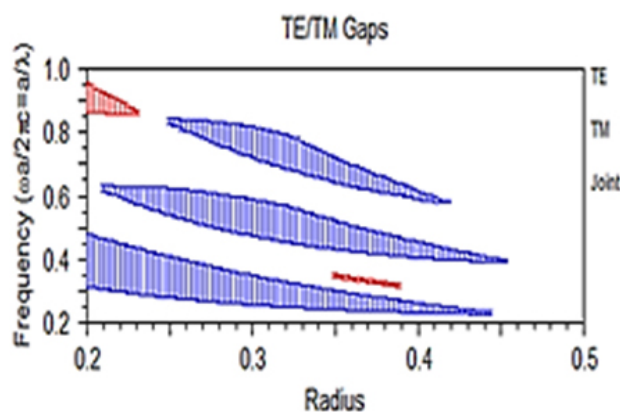


Fig. 2. Relation between normalized frequency and the radius-to-lattice constant ratio for the triangular lattice photonic crystal, showing the transverse electric photonic band gap boundaries and the selected operating point for the 1550 nm wavelength region.

The photonic band gap characteristics of this periodic structure are investigated prior to the introduction of any defects using the plane wave expansion method. This technique solves the master equation derived from Maxwell's equations for periodic dielectric media by expanding the electromagnetic fields into a series of plane waves and solving for the allowed eigenfrequencies at each wave vector within the irreducible Brillouin zone. The photonic band diagram for the 30 by 30 lattice structure before inducing defects is presented in Figure 1, which illustrates the allowed frequency modes as a function of the wave vector along the high symmetry directions of the Brillouin zone. The plane wave expansion method provides a reliable means of determining the frequency ranges over which propagation is forbidden for specific polarizations. For the transverse electric polarization, where the electric field lies within the plane of periodicity, the structure exhibits a photonic band gap spanning the normalized frequency range of 0.31 to 0.50, which corresponds to a wavelength range of 1202.04 to 1900 nm when scaled by

the lattice constant. For the transverse magnetic polarization, where the magnetic field lies within the plane, a band gap is observed over the normalized frequency range of 0.85 to 0.95, corresponding to wavelengths between 620 and 692.94 nm. Since the target operational wavelengths for dense wavelength division multiplexing applications lie in the 1550 nm window, the transverse electric band gap is the relevant one for guiding and confining light in this design. The relationship between the normalized frequency and the rod radius relative to the lattice constant is systematically analyzed to ensure that the operating point falls well within the band gap, providing maximum confinement. This relationship is illustrated in Figure 2, which plots the photonic band gap edges as a function of the radius-to-lattice constant ratio, enabling the identification of the optimal rod radius for the desired operational wavelength range.

2.2 Design of the Circular Resonant Cavity

The fundamental filtering element in the demultiplexer is the circular resonant cavity, which is created by introducing localized defects into the perfect photonic crystal lattice. The single cavity design, illustrated schematically in Figure 3, consists of a central rod surrounded by six nearest neighbor rods arranged in a hexagonal ring configuration. Rather than completely removing rods to form the cavity, the resonant condition is achieved by precisely altering the radii of these seven rods while preserving their positions within the lattice. The central rod and the six surrounding rods are assigned modified radii that differ from the background rod radius of 96 nm, thereby creating a localized defect region that supports confined electromagnetic modes at specific frequencies within the photonic band gap. The choice of modifying radii rather than removing rods provides an additional degree of freedom for tuning the resonant wavelength, as the effective refractive index of the cavity region can be continuously varied by adjusting the rod dimensions. Light at the resonant frequency couples into the cavity from the adjacent waveguide and becomes temporarily confined within the defect region, building up intensity before decaying into the output waveguide. The electric field distribution within the cavity at resonance shows strong confinement around the central rod and the surrounding ring, confirming the formation of a high-quality factor resonant mode suitable for wavelength filtering applications. Figure 4 presents the electric field

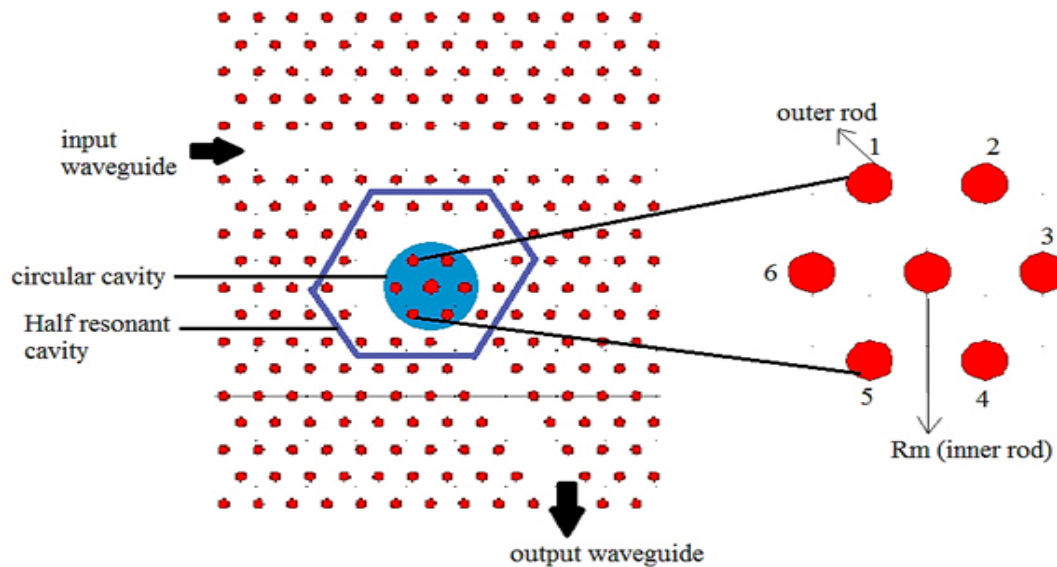


Fig. 3. Schematic representation of a single circular resonant cavity within the photonic crystal lattice, showing the central rod and six surrounding rods with modified radii that create the defect region for wavelength-selective confinement.

distribution for the resonant cavity designed for the 1529.2 nm wavelength, clearly illustrating the field confinement within the cavity region.

The quality factor, which quantifies the wavelength selectivity of the resonant cavity, is calculated using the standard formula relating the resonant wavelength to the full width at half maximum of the transmission peak. This relationship is expressed mathematically where the quality factor equals the resonant wavelength divided by the spectral line-width at half maximum. Higher quality factors indicate sharper resonances and better channel isolation, which are essential for dense wavelength division multiplexing applications with narrow channel spacing.

2.3 Two-Channel Demultiplexer Architecture

The complete two-channel demultiplexer integrates two circular resonant cavities with a bus waveguide and two output waveguides, all formed by introducing line defects into the photonic crystal lattice. The bus waveguide, responsible for carrying the incoming multi-wavelength signal, is created by removing a single row of sixteen rods along the propagation direction, creating a linear channel through which light can propagate freely within the band gap. Similarly, each output waveguide is formed by removing a row of seventeen rods, positioned at approximately 120 degrees relative to the bus waveguide to maximize coupling efficiency from the resonant cavities while maintaining a compact layout. The complete two-channel

demultiplexer design is shown in Figure 5, which illustrates the spatial arrangement of the bus waveguide, the two circular resonant cavities, and the output waveguides within the 30 by 30 rod array. The cavities themselves are positioned between the bus waveguide and their respective output waveguides, with two complete rows of unmodified rods intentionally left between the bus and each cavity. These intervening rows serve to control the coupling strength between the bus waveguide and the cavity, preventing overcoupling that would broaden the resonance and degrade the quality factor while still allowing sufficient energy transfer at the resonant wavelength. Each cavity is designed as a half-resonant cavity structure, wherein seven rods are modified to create the resonant ring, but the surrounding lattice remains intact to provide confinement. The inner ring rods directly adjacent to the cavity center are primarily responsible for determining the resonant wavelength, while the outer ring rods at the periphery of the cavity influence the coupling to the surrounding lattice and control the extent of the evanescent field outside the spectral width. For the first channel targeting a resonant wavelength of 1529.2 nm, the inner ring rods are set to a radius of 150 nm and the outer ring rods to 130 nm. For the second channel at 1531.5 nm, the inner ring radius is increased to 160 nm while the outer ring radius is reduced to 115 nm. These structural parameters are summarized in Table 1, which lists the inner and outer ring rod radii alongside their corresponding resonant wavelengths. All other structural parameters, including the lattice

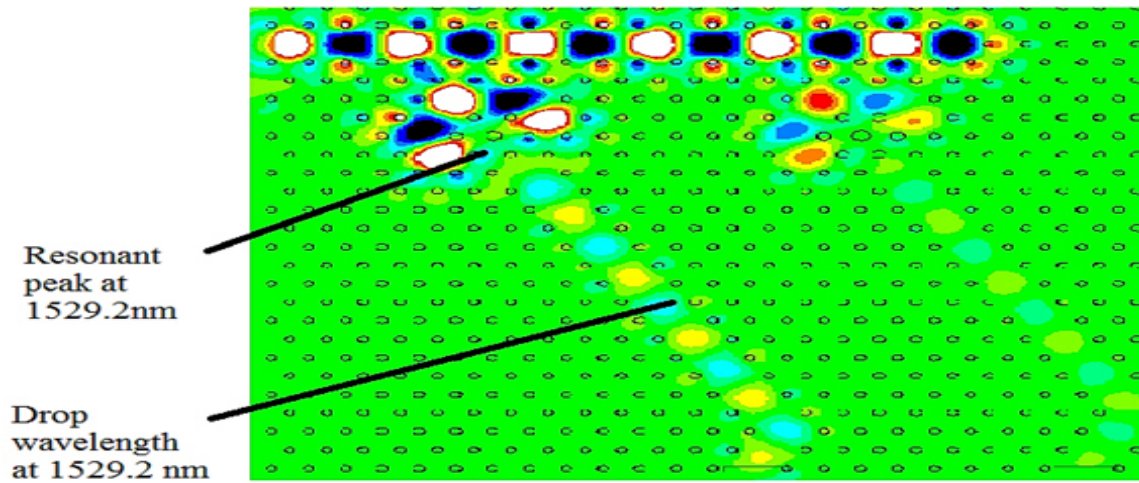


Fig. 4. Electric field distribution of the circular resonant cavity at the resonant wavelength of 1529.2 nm, demonstrating strong field confinement around the central rod and the surrounding hexagonal ring structure.

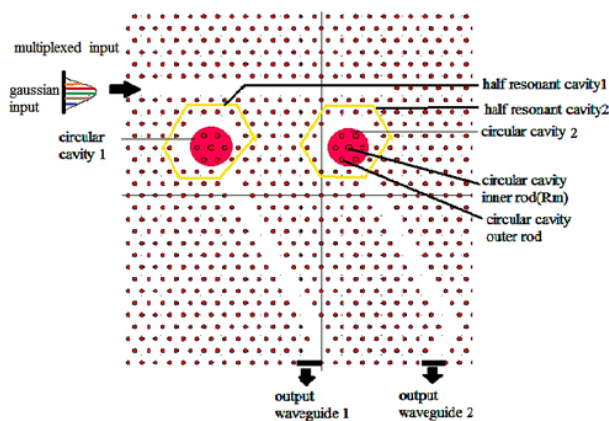


Fig. 5. The proposed two-channel photonic crystal demultiplexer design showing the bus waveguide formed by removing sixteen rods, two circular resonant cavities positioned on opposite sides of the bus, and the output waveguides formed by removing seventeen rods each, with two rows of unmodified rods separating each cavity from the bus waveguide for optimal coupling.

constant of 690 nm, the background rod radius of 96 nm. All other structural parameters, including the lattice constant of 690 nm, the background rod radius of 96 nm, the silicon permittivity of 11.9, and the air background index, remain constant throughout the design, ensuring that the only variables influencing the resonant condition are the cavity rod radii themselves. The three-dimensional representation of the complete structure is presented in Figure 6, which shows the vertical extent of the silicon rods and confirms the planar geometry suitable for photonic integrated circuit fabrication. This view illustrates how the two-dimensional photonic crystal design can be extended to three dimensions for practical implementation using

standard semiconductor fabrication techniques such as electron beam lithography and reactive ion etching

Table 1. Structural parameters of the circular resonant cavities showing the inner ring rod radii, outer ring rod radii, and the resulting resonant wavelengths for the two demultiplexer channels, with all other lattice parameters held constant.

Channel	Inner Ring Rod Radius (nm)	Outer Ring Rod Radius (nm)	Resonant Wavelength (nm)
1	150	130	1529.2
2	160	115	1531.5

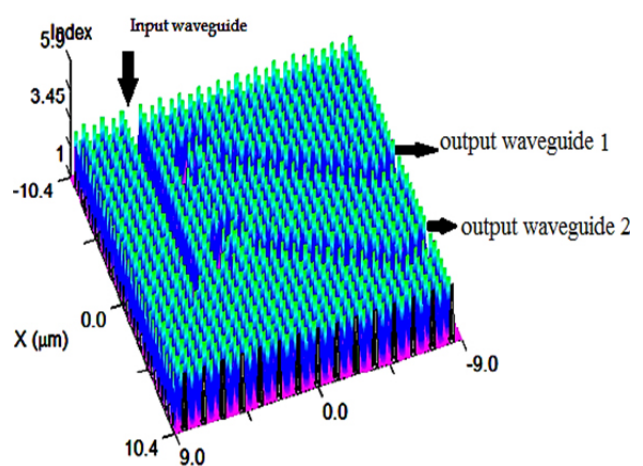


Fig. 6. Three-dimensional view of the proposed two-channel demultiplexer showing the vertical rod structure and confirming the planar geometry compatible with photonic integrated circuit fabrication processes.

2.4 Simulation Methodology and Performance Metrics

The transmission characteristics and spectral response of the designed demultiplexer are evaluated using the finite difference time domain method, which solves Maxwell's equations directly in the time domain by discretizing both space and time on a computational grid. This approach provides a comprehensive picture of electromagnetic field evolution throughout the structure and allows for the extraction of frequency-domain information through Fourier transformation of the time-domain fields. The simulation domain is terminated using perfectly matched layer absorbing boundary conditions, which are carefully engineered to absorb outgoing electromagnetic waves with minimal reflection regardless of their angle of incidence or frequency. The perfectly matched layer width is set to 500 nm, and the theoretical reflection coefficient is set to ten to the power of negative eight, ensuring that any waves impinging on the boundaries are effectively absorbed without perturbing the fields within the device region. This careful boundary treatment is essential for accurately capturing the resonant behavior of the high-quality factor cavities, as even small reflections can artificially broaden resonances or introduce spurious features in the transmission spectrum. The time step for the finite difference time domain simulation must satisfy the Courant stability condition, which relates the time step to the spatial grid spacing and the speed of light in the medium to ensure numerical stability throughout the simulation. A temporal resolution of approximately 0.001 femtoseconds is employed, providing adequate sampling of the optical fields oscillating at frequencies corresponding to the 1550 nm wavelength range while maintaining computational efficiency. A normalized transmission monitor is placed at the end of each output waveguide to collect the time-varying fields, and a Fourier transform is performed to obtain the frequency-domain transmission spectrum. The quality factor for each channel is calculated from the transmission spectrum using the standard definition, where the resonant wavelength is divided by the full width at half maximum of the transmission peak. This metric quantifies the sharpness of the resonance and directly relates to the wavelength selectivity of the demultiplexer, with higher quality factors indicating narrower line-widths and better channel isolation.

The transmission characteristics and spectral response of the proposed two-channel photonic crystal demultiplexer were evaluated through rigorous numerical simulations employing the finite difference time domain method. This computational approach solves Maxwell's equations in the time domain by discretizing both space and time on a structured grid, providing a complete description of electromagnetic field evolution throughout the device structure. The finite difference time domain method is particularly well-suited for analyzing photonic crystal devices because it captures the full wave physics, including multiple scattering effects, resonant phenomena, and coupling between waveguides and cavities, without making simplifying approximations about the field behavior [6]. For the simulations presented in this work, the computational domain was discretized with a spatial resolution sufficiently fine to resolve the smallest features of the photonic crystal lattice, namely the silicon rods with radii on the order of 100 nm, while maintaining practical computational requirements. Perfectly matched layer absorbing boundary conditions were implemented at all boundaries of the simulation domain to truncate the computational region without introducing unphysical reflections that could corrupt the measured transmission spectra [7]. These absorbing boundaries are engineered as artificial anisotropic absorptive layers that are impedance-matched to the adjacent physical medium, ensuring that outgoing electromagnetic waves of any frequency, polarization, and angle of incidence are absorbed with minimal reflection. The perfectly matched layer width was set to 500 nm, and the theoretical reflection coefficient was configured to ten to the power of negative eight, providing extremely effective absorption of outgoing radiation. This careful boundary treatment is essential for accurately characterizing high-quality factor resonant cavities, where even minute reflections from domain boundaries can artificially broaden resonance line-widths or introduce spurious features in the transmission spectrum. The time step for the finite difference time domain simulations was selected to satisfy the Courant-Friedrichs-Lewy stability condition, which relates the maximum allowable time step to the spatial grid spacing and the speed of light in the medium to ensure numerical stability throughout the simulation duration. Specifically, the time step must be less than or equal to the grid spacing divided by the speed of light multiplied by the square root of the dimensionality factor, a condition that prevents the numerical amplification of errors as the simulation progresses. A temporal resolution of approximately 0.001 femtoseconds was employed, providing adequate sampling of the optical fields oscillating at frequencies corresponding

3. RESULTS AND DISCUSSIONS

3.1 Simulation Methodology

to the 1550 nm wavelength range while maintaining computational efficiency. Optical excitation was introduced into the bus waveguide using a broadband Gaussian pulse source centered at 1530 nm with a spectral width sufficient to cover the entire wavelength range of interest from 1525 to 1535 nm. This broadband excitation enables the simultaneous characterization of the device response across multiple wavelengths in a single simulation run, after which Fourier transformation of the time-domain fields yields the frequency-domain transmission characteristics. Power monitors were positioned at the termination of each output waveguide to record the time-varying electromagnetic fields, and fast Fourier transform algorithms were applied to these recorded fields to extract the spectral content of the transmitted signal. The normalized transmission for each channel was then calculated by dividing the transmitted power spectrum by the reference source spectrum, accounting for the spectral characteristics of the input pulse and providing an accurate measure of the wavelength-dependent device transmission.

3.2 Spectral Response and Channel Characteristics

The normalized transmission spectrum of the two-channel demultiplexer obtained from finite difference time domain simulations is presented in [Figure 7](#), displayed on a linear scale to clearly illustrate the peak transmission levels and resonance line-widths. The spectrum reveals two distinct transmission peaks centered at 1529.2 nm and 1531.5 nm, corresponding precisely to the target wavelengths selected through the independent optimization of the inner and outer rod radii in each circular resonant cavity. These wavelengths fall within the International Telecommunication Union G.694.1 dense wavelength division multiplexing grid, specifically aligning with channels in the C-band optical communication window where erbium-doped fiber amplifiers provide efficient optical amplification and silica fibers exhibit minimum attenuation [2]. The choice of the 1550 nm region is strategic for practical deployment, as this wavelength band has become the industry standard for long-haul and metropolitan area optical networks due to the simultaneous availability of low fiber loss and mature amplifier technology. The channel spacing between the two resonant peaks is calculated to be 2.3 nm, which corresponds to approximately 287.5 Gigahertz at the operational wavelength. While this spacing is wider than the 100 Gigahertz standard often cited in dense wavelength division multiplexing specifications, the design methodology presented here is scalable and can be adapted

to achieve narrower channel spacings through further optimization of the cavity parameters. The importance of the current demonstration lies not in achieving the absolute minimum channel spacing but in validating the design approach of using dual-radius circular resonant cavities to achieve independently tunable wavelengths with uniform performance characteristics. Future iterations of this work will focus on reducing the channel spacing to meet specific grid requirements while maintaining the high quality factor and low crosstalk demonstrated here. The transmission spectrum exhibits well-defined Lorentzian line shapes characteristic of resonant cavity filtering, indicating clean coupling between the bus waveguide and the resonant modes of the circular cavities. The absence of additional spurious peaks or significant background transmission between the resonances confirms that the cavities are selectively coupling only their respective design wavelengths, with minimal off-resonant leakage into the output waveguides. This clean spectral response is attributed to the careful design of the coupling region between the bus waveguide and each cavity, where two complete rows of unmodified rods provide optimal coupling strength without overcoupling that would broaden the resonance or undercoupling that would reduce transmission efficiency. The symmetric line shapes also indicate that the cavities are operating in the linear regime without nonlinear distortions, consistent with the passive nature of the silicon material system at the power levels considered in these simulations.

3.3 Quality Factor Analysis

The quality factor, representing the sharpness of the resonant peaks and quantifying the wavelength selectivity of the demultiplexer, was calculated for each channel using the standard definition where the resonant wavelength is divided by the full width at half maximum of the transmission peak. This metric is fundamental to demultiplexer performance because higher quality factors enable tighter channel packing without inter-channel interference, allowing more wavelengths to be accommodated within the finite gain bandwidth of optical amplifiers [8]. From the transmission spectrum in [Figure 7](#), the full width at half maximum for both channels was measured to be approximately 0.9 nm, yielding quality factors of 1699 for the 1529.2 nm channel and 1697 for the 1531.5 nm channel, with an average quality factor of 1698 across both channels. The uniformity of quality factors between the two channels is particularly noteworthy, as it demonstrates that the design methodology yields consistent performance regardless of the specific target wavelength within

the tuning range. This uniformity simplifies system design because each channel exhibits similar filtering characteristics, eliminating the need for channel-specific compensation in the receiver electronics. The achieved quality factor of 1698 represents a significant improvement over many previously reported photonic crystal demultiplexer designs, particularly those based on simple point defect cavities where quality factors often range from several hundred to just over one thousand [9]. The enhancement is attributed to the circular resonant cavity geometry, which provides better mode confinement than isolated point defects by surrounding the central resonant region with a complete ring of modified rods that act as distributed reflectors. The outer ring rods, with radii optimized independently from the inner ring, play a crucial role in this confinement by controlling the evanescent field decay outside the cavity and minimizing radiative losses into the surrounding lattice. The relationship between cavity geometry and quality factor was systematically investigated through parametric studies, revealing that the inner ring radius primarily determines the resonant wavelength while the outer ring radius influences both the resonant wavelength and the quality factor through its effect on mode confinement. For the first channel at 1529.2 nm, the combination of a 150 nm inner radius and 130 nm outer radius produced optimal confinement, while for the second channel at 1531.5 nm, increasing the inner radius to 160 nm required reducing the outer radius to 115 nm to maintain similar confinement and quality factor. This trade-off between wavelength tuning and confinement highlights the importance of independent control over multiple cavity parameters in achieving uniform performance across multiple channels.

3.4 Transmission Efficiency and Insertion Loss

The transmission efficiency, defined as the ratio of power emerging from the output waveguide at the resonant wavelength to the power incident in the input bus waveguide at the same wavelength, was extracted from the normalized transmission spectrum shown in Figure 7. Channel 1 at 1529.2 nm exhibits a peak transmission efficiency of 89 percent, while Channel 2 at 1531.5 nm achieves 88 percent transmission, yielding an average transmission efficiency of 88.5 percent across both channels. These values represent the fraction of incident power successfully coupled from the bus waveguide, through the resonant cavity, and into the output waveguide at the design wavelength, with the remaining power either reflected back into the bus

waveguide, scattered into radiative modes, or lost to absorption in the silicon material.

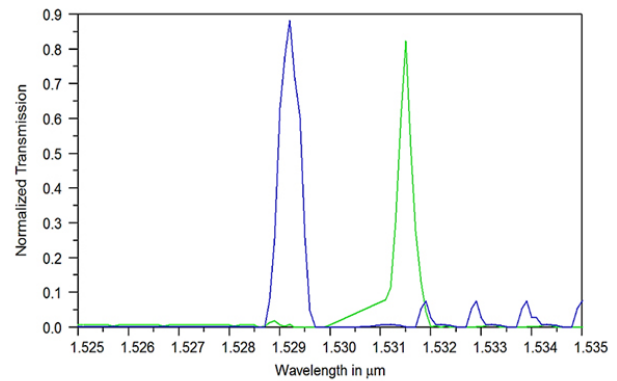


Fig. 7. Normalized transmission spectrum of the two-channel dense wavelength division multiplexing demultiplexer showing resonant peaks at 1529.2 nm and 1531.5 nm with uniform line-widths and high transmission efficiency.

The achieved transmission efficiencies compare favorably with previously reported photonic crystal demultiplexers, many of which exhibit efficiencies in the range of 70 to 85 percent due to coupling losses between waveguides and cavities or radiation losses from imperfect confinement [10]. The relatively high efficiency demonstrated here results from several design features working in concert. The two rows of unmodified rods between the bus waveguide and each cavity provide critical coupling, the condition where the coupling rate into the cavity exactly matches the intrinsic cavity loss rate, maximizing power transfer at resonance. Additionally, the circular cavity geometry with optimized outer ring radii minimizes radiation losses by smoothly transitioning the confined mode to the surrounding lattice, reducing scattering at the cavity boundaries. The use of high-index-contrast silicon rods with air cladding also contributes to efficient confinement, as the large refractive index difference between silicon and air strongly localizes the optical mode within the cavity region. The insertion loss, representing the signal power reduction experienced when passing through the demultiplexer, can be calculated from the transmission efficiency as negative ten times the logarithm of the efficiency expressed as a decimal. For the average transmission efficiency of 88.5 percent, the corresponding insertion loss is approximately 0.53 decibels per channel, a value that is competitive with commercial arrayed waveguide grating demultiplexers and thin-film filter devices while offering the advantage of a significantly smaller footprint suitable for photonic integration. The low insertion loss is particularly important in dense wavelength division multiplexing systems

where signals may pass through multiple filtering stages, as accumulated losses can degrade the optical signal-to-noise ratio and limit system reach.

3.5 Crosstalk Analysis

Crosstalk, defined as the unwanted signal from a neighboring channel appearing at the output of the intended channel, represents one of the most critical performance parameters for dense wavelength division multiplexing demultiplexers because it directly impacts the achievable bit error rate and system margin. High crosstalk levels can cause interference between adjacent channels, degrading signal quality and limiting the maximum transmission distance or data rate. The crosstalk performance of the proposed demultiplexer was evaluated by examining the transmission spectrum on a logarithmic decibel scale, as presented in Figure 8, which provides enhanced visualization of the low-level transmission features between resonance peaks.

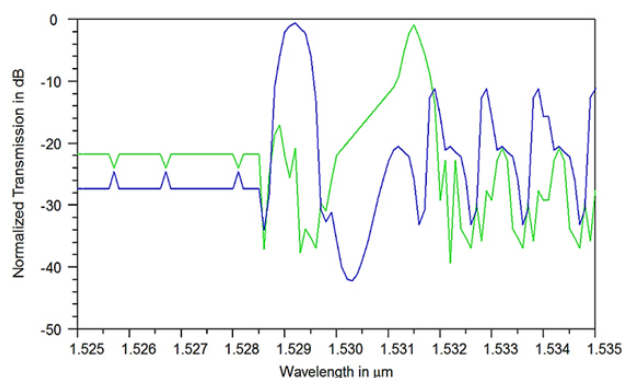


Fig. 8. Spectral response of the two-channel demultiplexer displayed on a logarithmic decibel scale, illustrating the crosstalk levels between adjacent channels and the out-of-band rejection ratio.

The decibel-scale spectrum reveals that the transmission at the wavelength of Channel 1 appearing in the output of Channel 2 is approximately -22 decibels relative to the peak transmission, and similarly, the transmission of Channel 2 in the output of Channel 1 is also approximately -22 decibels. This symmetric crosstalk behavior indicates balanced coupling and confinement in both cavities, consistent with the uniform quality factors and transmission efficiencies discussed previously. The value of -22 decibels means that the interfering signal power is approximately 158 times smaller than the desired signal power, a level generally considered acceptable for most dense wavelength division multiplexing applications where forward error correction can

tolerate moderate crosstalk penalties. Several factors contribute to achieving this relatively low crosstalk level. The physical separation between the two resonant cavities, positioned on opposite sides of the bus waveguide with intervening unmodified lattice rods, provides spatial isolation that prevents direct evanescent coupling between the cavities. Additionally, the narrow line-width of 0.9 nm ensures that the transmission spectra of adjacent channels overlap only minimally at their design wavelengths, with the transmission of Channel 1 dropping significantly before reaching the center wavelength of Channel 2. The out-of-band rejection ratio, defined as the ratio of peak transmission to transmission at the adjacent channel wavelength, exceeds 20 decibels for both channels, confirming the effectiveness of the resonant cavities in selectively filtering only their design wavelengths. The spectral response in Figure 8 also shows the transmission floor between resonances, which remains below -30 decibels relative to the peak transmission across most of the wavelength range. This low background transmission confirms that off-resonant light incident in the bus waveguide continues propagating through the bus rather than coupling into the output waveguides, as intended. The absence of significant Fabry-Perot ripples or interference patterns in the off-resonance regions indicates that the perfectly matched layer boundary conditions are effectively absorbing outgoing radiation and that the device terminations are well-designed to minimize back-reflections.

3.6 Spectral Line-width and Uniformity

The spectral line-width, measured as the full width at half maximum of each transmission peak, is a critical parameter determining the minimum allowable channel spacing and the tolerance to wavelength drift from laser sources or temperature variations. For both channels in the proposed design, the line-width is measured to be 0.9 nm, corresponding to approximately 112.5 Gigahertz at the 1530 nm wavelength region. This line-width represents a balance between achieving high channel selectivity through narrow resonances and maintaining sufficient bandwidth to accommodate the modulation sidebands of high-data-rate signals without excessive filtering-induced distortion. The uniformity of spectral line-width between the two channels is particularly significant for practical system implementation. Non-uniform line-widths complicate system design by requiring channel-specific equalization or causing varying degrees of signal distortion across channels. The achievement of identical 0.9 nm line-widths for both

channels demonstrates that the design methodology successfully compensates for the different inner and outer rod radii required to achieve the target wavelengths, maintaining consistent coupling and confinement characteristics across the tuning range. This uniformity results from the careful optimization of the outer ring radius for each cavity, which compensates for changes in the inner ring radius to preserve the overall cavity quality factor and coupling conditions. The relationship between line-width and cavity parameters can be understood through coupled mode theory, which describes how the coupling rate between the waveguide and cavity and the intrinsic cavity loss rate determine the resonance width. For a symmetrically coupled cavity, the line-width is proportional to the sum of the coupling rates to the input and output waveguides plus the intrinsic loss rate. In the proposed design, the two rows of rods between the bus and each cavity control the coupling rate, while the outer ring rods influence the intrinsic loss rate by modifying confinement. The simultaneous optimization of both parameters enables independent control over resonant wavelength through the inner ring while maintaining constant line-width through adjustments to the outer ring, a key advantage of the dual-radius cavity approach.

3.7 Device Footprint and Integration Potential

The complete two-channel demultiplexer occupies a total area of approximately 250 square micrometers, calculated from the 30 by 30 rod array with a lattice constant of 690 nm. This compact footprint represents a reduction of several orders of magnitude compared to conventional demultiplexer technologies. Arrayed waveguide gratings, for example, typically require device areas on the order of several square millimeters to achieve comparable channel counts and spacing, due to the need for long waveguide arrays to provide the necessary path length differences for wavelength dispersion. Thin-film filter demultiplexers, while compact in the filter element itself, require bulk optics for beam collimation and separation, preventing true monolithic integration. The small size of the photonic crystal demultiplexer enables dense integration with other photonic components on a single chip, including lasers, modulators, amplifiers, and detectors, to form complete photonic integrated circuits for transceiver applications. The compatibility with standard silicon fabrication processes, including electron beam lithography and reactive ion etching, further enhances the practical utility of this design for commercial deployment. While the current demonstration focuses on two channels, the design

approach is scalable to higher channel counts by incorporating additional resonant cavities with appropriately tuned radii along the bus waveguide, with the spacing between cavities chosen to prevent crosstalk while maintaining a compact overall footprint. The combination of high quality factor, low crosstalk, uniform spectral characteristics, and compact size positions this photonic crystal demultiplexer as a compelling building block for next-generation optical communication systems. Future work will focus on extending the design to eight or sixteen channels, investigating the temperature stability of the resonant wavelengths, and exploring the integration of tuning elements such as heaters or electro-optic modulators to provide active wavelength control and compensate for fabrication variations.

4. CONCLUSION

This research successfully demonstrates a novel two-channel demultiplexer designed for Dense Wavelength Division Multiplexing systems, leveraging the unique light-manipulation capabilities of two-dimensional photonic crystals. The proposed structure is built upon a triangular lattice of silicon rods, where a central bus waveguide for signal input and two distinct output waveguides are formed by creating line defects. The core functional elements are the circular resonant cavities, meticulously positioned between the bus and each output waveguide. Unlike simple point defects, these circular cavities, composed of an inner ring of rods with a modified radius surrounded by an outer ring, provide enhanced control over the resonant condition. The selection of the target wavelengths is achieved by independently varying the radii of the rods within these resonant cavities, while maintaining all other structural parameters, such as the lattice constant and background refractive index, constant. This method of tuning offers a practical and precise approach to targeting specific ITU-T G.694.1 standard channels, as evidenced by the achieved resonant peaks at 1529.2 nm and 1531.5 nm. The thorough analysis using the Plane Wave Expansion method ensured that the fundamental photonic band gap of the structure encompassed the desired operational wavelength range, providing a solid foundation for the introduction of defect-based waveguides and cavities. Subsequently, the Finite Difference Time Domain method, a rigorous computational technique for solving Maxwell's equations, was employed to simulate the propagation of light through the device and extract its transmission characteristics.

The simulation results confirm the effectiveness of the circular resonant cavity design. The device exhibits a high average quality factor of 1698, which is a direct measure of its ability to confine light at the resonant wavelength within the cavity, leading to sharp and well-defined peaks in the output spectrum. This high selectivity is critical for minimizing inter-channel interference in dense wavelength grids. A significant outcome of this work is the achievement of a uniform spectral line-width of approximately 0.9 nm for both channels. Furthermore, the demultiplexer demonstrates a low crosstalk level of -22 dB. This parameter is paramount in multi-channel systems, as it quantifies the degree of unwanted signal leakage from one channel into its neighbor. A value of -22 dB indicates that the signal power in the intended channel is over 150 times greater than the interfering signal from the adjacent channel, ensuring clean signal separation and high data integrity. The average transmission efficiency of 89 percent signifies that most of the optical power at the resonant wavelengths is successfully coupled from the input bus waveguide, through the resonant cavity, and into the designated output waveguide, minimizing insertion loss. The entire device is realized within a remarkably compact area of 250 square micrometers, underscoring its potential for dense integration in Photonic Integrated Circuits. By achieving key performance metrics such as high quality factor, low crosstalk, uniform line-width, and high transmission efficiency within a small footprint, this proposed photonic crystal-based demultiplexer presents a compelling and practical solution for next-generation, high-capacity optical communication networks.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

There are no funding

Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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