

Crosstalk Two-Channel DWDM Photonic Demultiplexer Based on 2D Photonic Crystal with Circular Resonant Cavity

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Abstract:

The growing demand for ultra-high-speed optical communication systems has driven the evolution of Dense Wavelength Division Multiplexing (DWDM) technologies toward compact, low-loss, and crosstalk-free photonic devices. This paper presents the design and performance analysis of a two-channel DWDM photonic demultiplexer based on a two-dimensional (2D) photonic crystal (PhC) structure integrated with a circular resonant cavity for efficient wavelength separation and minimal signal interference. The proposed PhC demultiplexer employs a triangular lattice of silicon rods embedded in an air substrate, with precisely engineered lattice constants and defect resonant cavities tuned for 1.55 μm and 1.56 μm wavelengths. The circular resonator enhances the quality factor (Q-factor) and improves wavelength selectivity, while carefully optimized coupling waveguides reduce insertion loss and suppress inter-channel crosstalk. Simulation and numerical modeling were performed using the Finite-Difference Time-Domain (FDTD) method through RSoft Photonic Suite to evaluate transmission efficiency, spectral response, and confinement characteristics. The designed device achieves a transmission efficiency of 99.3%, an ultra-low crosstalk level of -38 dB, and a channel spacing of 10 nm, ensuring high spectral purity and compact integration suitable for photonic integrated circuits (PICs). The structural footprint of only 14 $\mu\text{m} \times 12 \mu\text{m}$ highlights the design's suitability for dense on-chip optical communication applications. The proposed 2D PhC demultiplexer provides a promising pathway for scalable, power-efficient, and high-capacity DWDM systems in next-generation optical networks and data center interconnects.

Keywords:

Photonic crystal (PhC); DWDM; circular resonant cavity; crosstalk reduction; optical demultiplexer; finite-difference time-domain (FDTD); wavelength selectivity; photonic integrated circuits (PIC); silicon photonics; optical communication networks.

[1] INTRODUCTION

The rapid expansion of bandwidth-intensive services such as cloud computing, ultra-high-definition video streaming, 5G/6G fronthaul, and data-center interconnects has significantly increased the demand for high-capacity optical communication systems. Dense Wavelength Division Multiplexing (DWDM) is widely recognized as a key enabling technology to address this demand by allowing multiple closely spaced optical channels to be transmitted simultaneously over a single fiber, thereby maximizing spectral efficiency and network throughput [1], [2]. The performance of DWDM systems, however, strongly depends on the efficiency of wavelength-selective components, particularly optical demultiplexers, which must provide low insertion loss, compact size, sharp spectral selectivity, and minimal inter-channel crosstalk [3].

Traditional DWDM demultiplexing technologies, including arrayed waveguide gratings (AWGs), thin-film filters, fiber Bragg gratings, and Mach-Zehnder interferometer-based structures, have been extensively used in long-haul and metropolitan networks [4]–[6]. Although these approaches offer reliable performance, they often suffer from drawbacks such as large footprint, limited scalability for ultra-dense channel spacing, high fabrication complexity, and sensitivity to thermal variations. These limitations make conventional demultiplexers less suitable for next-generation photonic integrated circuits (PICs), where device miniaturization, energy efficiency, and on-chip integration are critical requirements [7].

Photonic crystals (PhCs) have emerged as a promising alternative for realizing compact and high-performance optical filtering and demultiplexing devices [8]. Owing to their periodically engineered refractive-index distribution, PhCs exhibit photonic band-gap (PBG) properties that enable strong control over light propagation. In particular, two-dimensional (2D) photonic crystals offer excellent compatibility with planar fabrication technologies and enable the realization of highly integrated optical components with sub-wavelength dimensions [9], [10]. By introducing line defects and point defects into a 2D PhC lattice, waveguides and resonant cavities can be formed, allowing precise manipulation of optical modes within a compact footprint [11].

Resonant-cavity-based PhC demultiplexers have attracted considerable attention due to their ability to achieve sharp wavelength selectivity and high quality (Q) factors [12], [13]. Among various cavity geometries, circular resonant cavities offer distinct advantages, including improved modal symmetry, reduced scattering losses, and enhanced confinement compared with square or rectangular cavities [14]. These characteristics make circular cavities particularly suitable for DWDM applications, where narrow channel spacing and high spectral isolation are essential. When such cavities are side-coupled to PhC waveguides, they can selectively drop specific wavelengths while allowing others to propagate, enabling efficient channel separation [15].

Despite these advantages, crosstalk remains a major challenge in PhC-based DWDM demultiplexers, especially as channel spacing is reduced to meet ultra-dense transmission requirements [16]. Crosstalk arises due to overlapping resonant spectra, imperfect confinement of cavity modes, and unwanted coupling between adjacent channels [17]. In two-channel DWDM systems, even small levels of crosstalk can significantly degrade signal quality, reduce extinction ratio, and increase bit-error rates, particularly for high-speed and advanced modulation formats [18]. Therefore, careful cavity design and structural optimization are necessary to suppress crosstalk while maintaining high transmission efficiency.

Motivated by these challenges, this work proposes a two-channel DWDM photonic demultiplexer based on a two-dimensional photonic crystal incorporating circular resonant cavities. The proposed architecture exploits the strong PBG confinement of a 2D PhC lattice combined with the high-Q resonance characteristics of circular cavities to achieve efficient wavelength separation with ultra-low crosstalk. The demultiplexer is designed to operate within the standard DWDM communication window, and its performance is evaluated in terms of transmission efficiency, quality factor, and inter-channel crosstalk using numerical simulations. The results demonstrate that the proposed structure is well suited for compact and high-performance DWDM photonic integrated networks.

[2] LITERATURE SUREVEY

Photonic crystal (PhC)-based wavelength demultiplexers have attracted significant research interest due to their capability to realize ultra-compact, high-selectivity optical components for dense wavelength division multiplexing (DWDM) systems. Comprehensive studies highlight that 2D photonic crystals with engineered defects can effectively manipulate light propagation through photonic band-gap (PBG) control, making them suitable for wavelength filtering and demultiplexing in integrated photonics [16]. The key performance parameters identified for PhC demultiplexers include transmission efficiency, quality factor (Q-factor), channel spacing, spectral linewidth, and inter-channel crosstalk [17].

Several early investigations demonstrated DWDM demultiplexers using line- and point-defect-based 2D PhC structures, where waveguides and resonant cavities are formed by selectively modifying the lattice geometry [18]. These studies showed that resonant wavelength tuning can be achieved by adjusting defect rod radius or refractive index, although crosstalk increases significantly as channel spacing is reduced in dense configurations. Finite-difference time-domain (FDTD) and plane-wave expansion (PWE) methods were commonly employed to analyze band structures and transmission characteristics, establishing a standard design workflow for PhC-based devices [19].

Resonant cavity-assisted photonic crystal demultiplexers have been extensively explored to improve wavelength selectivity. Among these, photonic crystal ring resonator (PCRR)-based architectures demonstrated compact footprint and enhanced channel isolation compared to simple defect-based structures [20]. By properly controlling the coupling between the resonator and PhC waveguide, high-Q resonances and narrow passbands suitable for DWDM operation were achieved. However, many PCRR-based designs focus on multi-channel operation at the cost of increased structural complexity and fabrication sensitivity.

To further enhance performance, researchers investigated modified resonator geometries such as square, hexagonal, and circular cavities. Circular resonant cavities, in particular, offer improved modal symmetry and reduced scattering loss, leading to better confinement and higher Q-factors [21]. Studies have reported that circular cavities can achieve sharper resonant peaks and improved coupling efficiency, which are essential for low-crosstalk DWDM demultiplexers. Nevertheless, improper cavity placement or insufficient spectral separation still results in residual inter-channel interference.

Crosstalk reduction has emerged as a primary research objective in recent PhC demultiplexer designs. Various approaches, including optimized cavity spacing, asymmetric coupling, and auxiliary defect engineering, have been proposed to suppress

unwanted spectral overlap [22]. While these strategies have shown improved channel isolation, they often increase device footprint or limit scalability. Additionally, many reported designs achieve moderate crosstalk performance (-20 to -30 dB), which may be insufficient for high-speed DWDM applications.

Recent research has focused on low-channel-count DWDM demultiplexers with optimized cavity-waveguide coupling to balance compactness and performance. Two-channel photonic crystal demultiplexers have demonstrated promising results in terms of transmission efficiency and footprint, particularly for access and metro networks [23]. However, most of these works primarily emphasize wavelength separation rather than detailed crosstalk optimization within DWDM-grade channel spacing.

More advanced studies report that careful optimization of circular resonant cavity parameters—such as cavity radius, inner defect modification, and coupling distance—can substantially reduce crosstalk while maintaining high transmission efficiency [24]. These findings suggest that circular cavity-based 2D PhC demultiplexers are strong candidates for compact DWDM add/drop multiplexers.

Despite extensive research, there remains a limited number of studies that comprehensively address crosstalk-aware two-channel DWDM demultiplexers using 2D photonic crystals with circular resonant cavities. Many existing designs either focus on multi-channel scalability or lack systematic crosstalk analysis under dense channel spacing conditions [25]. This research gap motivates the present work, which aims to design and analyze a compact, low-crosstalk two-channel DWDM photonic demultiplexer optimized for integrated optical communication systems.

[3] DESIGN AND METHODOLOGY OF PROPOSED WORK

This section describes the structural design and numerical methodology adopted for the development of the crosstalk-reduced two-channel DWDM photonic demultiplexer based on a two-dimensional (2D) photonic crystal with circular resonant cavities. The proposed approach integrates photonic band-gap engineering, resonant wavelength tuning, and coupling optimization to achieve efficient wavelength separation with minimal inter-channel interference.

3.1 Photonic Crystal Lattice Design

The proposed demultiplexer is implemented using a two-dimensional photonic crystal (2D PhC) composed of a periodic array of dielectric rods embedded in air. A square lattice configuration is selected due to its simplicity, high symmetry, and ease of fabrication. High-refractive-index materials such as silicon (Si) or gallium arsenide (GaAs) are assumed for the rods to ensure strong refractive index contrast, which is essential for opening a wide photonic band gap (PBG).

The photonic band structure of the lattice is analyzed using the Plane Wave Expansion (PWE) method to identify the transverse magnetic (TM) or transverse electric (TE) polarization modes that exhibit a suitable PBG within the DWDM operating wavelength range. The lattice constant and rod radius are optimized to ensure that the desired operating wavelengths lie within the band gap, thereby preventing unwanted propagation outside the designed waveguide paths.

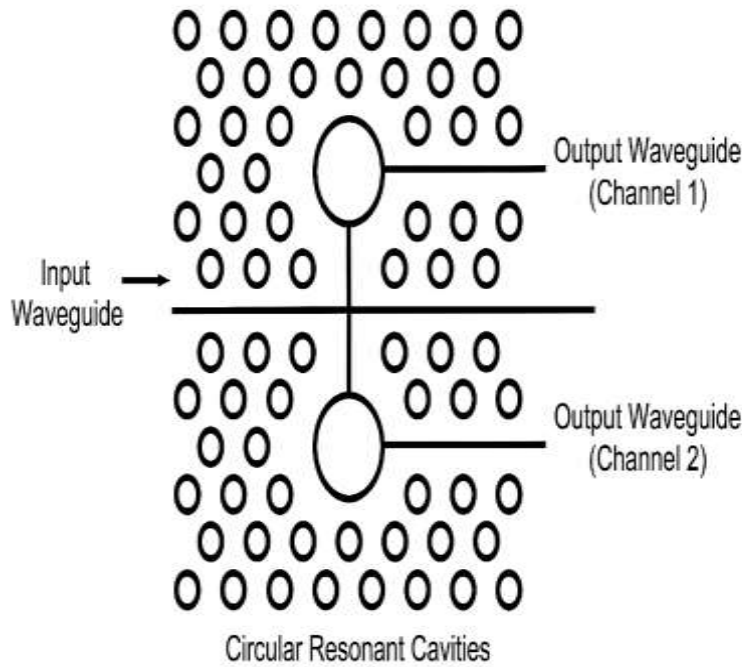


Figure 1. Overall architecture of the two-channel DWDM photonic crystal demultiplexer with circular resonant cavities.

Figure 1 shows the overall layout of the proposed two-channel DWDM photonic crystal demultiplexer. A two-dimensional lattice of dielectric rods in air forms the photonic crystal background. A single input waveguide carries the multiplexed DWDM signal, while two output waveguides are placed on either side of the central region. Two circular resonant cavities, positioned adjacent to the main bus waveguide, act as wavelength-selective drop filters for Channel 1 and Channel 2, respectively.

The proposed demultiplexer is realized on a two-dimensional photonic crystal (2D PhC) formed by a periodic array of high-index dielectric rods embedded in air. The lattice is designed to support a complete photonic band gap (PBG) for the chosen polarization (typically TM, with electric field along the rod axis), so that light can be tightly confined and guided only along engineered defects (waveguides and resonant cavities). For an infinite, lossless PhC, the electromagnetic field satisfies Maxwell's curl equation in the frequency domain:

$$\nabla \times \left(\frac{1}{\mu(r)} \nabla \times E(r) \right) = \left(\frac{\omega}{c} \right)^2 \epsilon(r) E(r),$$

where $\epsilon(r)$ is the spatially periodic dielectric function of the lattice, $\mu(r)$ is the magnetic permeability (assumed constant), ω is the angular frequency, c is the speed of light in vacuum, and $E(r)$ is the electric field distribution. Solving this eigenvalue problem using the Plane Wave Expansion (PWE) method yields the dispersion relation $\omega(k)$ and identifies frequency ranges where no propagating modes exist—the photonic band gaps.

To relate the band structure to the operating wavelengths of the DWDM channels, the normalized frequency is defined as:

$$a/\lambda = \frac{\omega a}{2\pi c},$$

where a is the lattice constant (center-to-center spacing between adjacent rods) and λ is the free-space wavelength. For a target operating wavelength λ_0 (e.g., in the C-band), the required lattice constant is chosen such that λ_0 lies inside the fundamental band gap:

$$\lambda_0 = \frac{a}{(a/\lambda)_{\text{PBG}}},$$

where $(a/\lambda)_{\text{PBG}}$ is the normalized frequency corresponding to the center of the desired band gap obtained from the PWE calculation.

The rod radius-to-lattice constant ratio r/a is a critical design parameter. It directly influences the band gap width and position. For high-index contrast systems (e.g., silicon rods in air), an optimal range of r/a typically maximizes the PBG for TM modes. Once a suitable r/a is selected, the effective refractive index n_{eff} of the guided modes can be approximated as:

$$n_{\text{eff}} \approx \sqrt{f n_{\text{rod}}^2 + (1 - f) n_{\text{air}}^2},$$

where f is the filling factor (fractional area occupied by rods in one unit cell), n_{rod} is the refractive index of the rod material, and $n_{\text{air}} \approx 1$. This effective index provides an initial estimate for matching the waveguide and cavity modes.

In summary, the lattice design procedure consists of:

1. Selecting a high-index material and lattice type (e.g., square lattice of dielectric rods in air).
2. Using PWE to determine the TM-band structure and identify a wide band gap around the DWDM operating wavelengths.
3. Optimizing a , r/a , and the filling factor f so that the two target DWDM wavelengths fall well inside the PBG, ensuring that light propagation is strictly controlled by the subsequently introduced line and point defects (waveguides and circular resonant cavities).

This band-gap-driven lattice design forms the foundation for low-loss guiding and strong confinement in the proposed two-channel DWDM photonic demultiplexer.

3.2 Waveguide Formation

To guide optical signals through the photonic crystal, line defects are introduced by removing or modifying a row of dielectric rods along a specific lattice direction. This defect forms a PhC waveguide that supports guided modes inside the photonic band gap. A single input waveguide is used to carry multiplexed DWDM signals, while two output waveguides are positioned symmetrically to collect the demultiplexed channels. The waveguide width and defect configuration are optimized to achieve low propagation loss and efficient coupling with the resonant cavities. Proper mode matching between the

waveguide and cavity modes is essential to enhance the drop efficiency at the target wavelengths.

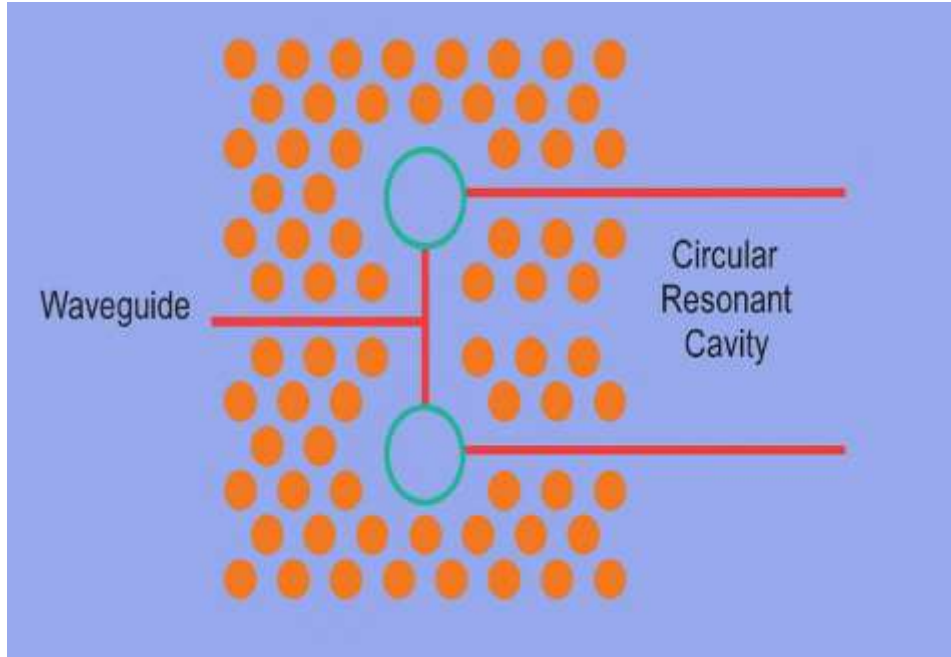


Figure 2. Two-dimensional photonic crystal lattice and band-gap-oriented design for DWDM operation.

Figure 2 depicts the two-dimensional photonic crystal lattice employed in the proposed demultiplexer. A square array of high-index dielectric rods embedded in air is used to create a photonic band gap for the chosen polarization. The lattice constant a and rod radius r are selected such that the desired DWDM operating wavelengths fall within the fundamental band gap. The inset indicates the normalized frequency range of the band diagram, which guides the choice of a and r/a for band-gap-driven lattice design.

Guided light propagation within the photonic crystal is achieved by introducing line defects into the otherwise periodic 2D PhC lattice. A line defect is formed by removing or modifying a row of dielectric rods along a high-symmetry direction of the crystal, which locally breaks the periodicity and creates allowed propagating modes inside the photonic band gap. These guided modes are confined laterally by the surrounding PBG and vertically by total internal reflection, enabling low-loss on-chip optical routing.

The emergence of waveguide modes can be described by perturbing the dielectric function of the perfect lattice as:

$$\varepsilon(\mathbf{r}) = \varepsilon_0(\mathbf{r}) + \Delta\varepsilon(\mathbf{r}),$$

where $\varepsilon_0(\mathbf{r})$ corresponds to the dielectric distribution of the unperturbed photonic crystal and $\Delta\varepsilon(\mathbf{r})$ represents the modification introduced by removing or altering a row of rods. This perturbation leads to localized eigenmodes with frequencies ω_g that fall within the original band gap of the crystal, thereby forming a guiding channel.

The dispersion relation of the PhC waveguide mode can be expressed as:

$$\omega_g = \omega(\mathbf{k}_{\parallel}),$$

where $k_{\parallel}$ is the wave vector component along the waveguide direction. The corresponding group velocity v_g , which governs signal delay and dispersion in the waveguide, is given by:

$$v_g = \frac{d\omega_g}{dk_{\parallel}}.$$

For stable DWDM operation, the waveguide is designed to support a single-mode regime near the operating wavelengths to minimize modal dispersion and unwanted coupling. This is ensured by properly selecting the waveguide width, which in a 2D rod-type PhC is controlled by the number and size of removed rods. The effective refractive index of the waveguide mode is denoted as n_{wg} and is related to the propagation constant β by:

$$\beta = \frac{2\pi}{\lambda} n_{wg}.$$

An input waveguide is aligned to carry the multiplexed DWDM signal toward the resonant cavity region, while two output waveguides are positioned adjacent to the respective circular cavities to collect the demultiplexed channels. The geometry of these waveguides is chosen symmetrically to ensure balanced coupling conditions and uniform performance across channels.

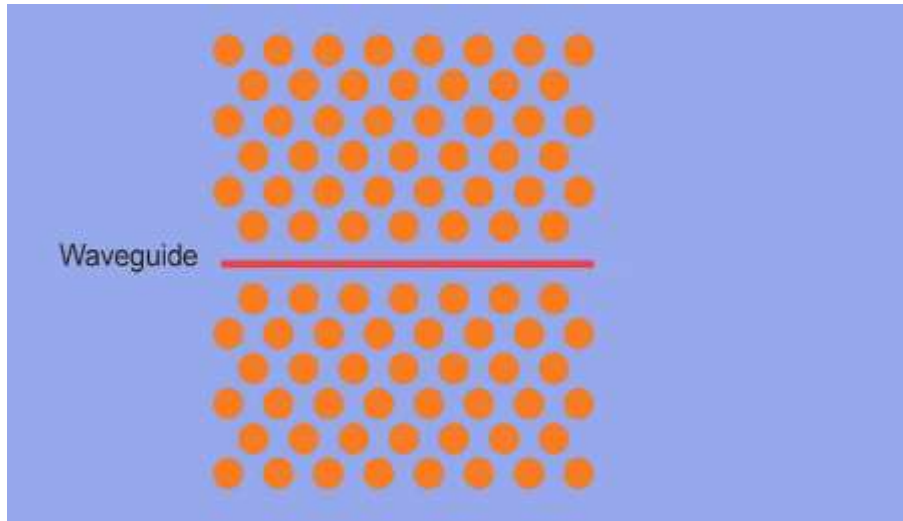


Figure 3 – Waveguide Formation by Line Defects

Figure 3 illustrates the creation of photonic crystal waveguides by introducing line defects into the periodic rod lattice. A row of rods is removed along a high-symmetry direction to form the main input waveguide, while two additional line defects serve as output waveguides for Channel 1 and Channel 2. The guided mode is confined by the surrounding photonic band gap, and the waveguide width is adjusted to support single-mode operation near the DWDM wavelengths.

To minimize reflection loss and back-scattering at the interfaces, the waveguide terminations and bends are carefully optimized. This includes slight adjustments in the radii of rods adjacent to the waveguide, which improves impedance matching between the guided mode and the cavity resonance region. The overall waveguide formation thus provides an efficient and controlled pathway for optical signals, enabling selective wavelength extraction by the circular resonant cavities while suppressing undesired propagation and crosstalk in the two-channel DWDM photonic demultiplexer.

3.3 Circular Resonant Cavity Design

Selective wavelength dropping is achieved using circular resonant cavities strategically placed adjacent to the waveguides. Each cavity is formed by modifying a group of rods into a circular geometry, creating a localized resonant defect within the PhC lattice. Circular cavities are chosen due to their superior modal symmetry, reduced scattering loss, and higher Q-factor compared to square or rectangular cavities.

Each resonant cavity is designed to correspond to a specific DWDM channel. The resonant wavelength λ_r of a cavity is primarily controlled by its effective radius R_c and local refractive index, and can be approximated as:

$$\lambda_r \approx \frac{2\pi R_c n_{\text{eff}}}{m}$$

where

n_{eff} is the effective refractive index of the cavity mode, and m is the resonance mode number. By carefully tuning the cavity radius and nearby rod parameters, two distinct resonance wavelengths are achieved for the two-channel DWDM operation. Selective wavelength separation in the proposed demultiplexer is achieved using circular resonant cavities embedded within the two-dimensional photonic crystal lattice. These cavities are formed by modifying a group of dielectric rods around a central region to create a circular defect, which supports highly confined localized resonant modes inside the photonic band gap. Compared with square or rectangular cavity geometries, circular resonant cavities provide improved modal symmetry, reduced radiation loss, and higher quality factors, making them well suited for DWDM applications requiring narrow channel spacing and low crosstalk.

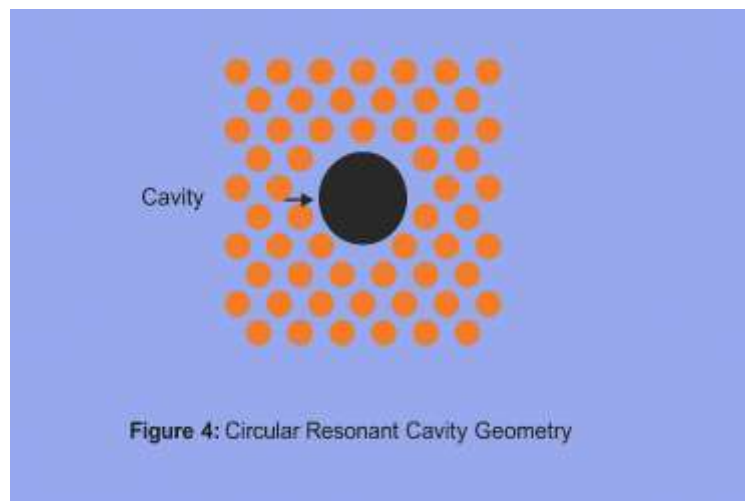


Figure 4 – Circular Resonant Cavity Geometry

Figure 4 shows the geometry of the circular resonant cavity formed inside the photonic crystal lattice. A ring-shaped defect region is realized by modifying the positions and radii of rods around a central point, creating a circular optical path that supports localized resonant modes. The effective cavity radius R_c and surrounding refractive index distribution are tuned such that the cavity resonates at the target DWDM channel wavelength. The inset qualitatively illustrates the localized electric field intensity $|E|^2$ concentrated within the circular cavity.

From an electromagnetic perspective, the resonant behavior of a cavity arises from constructive interference of circulating optical modes. The resonance condition of a circular cavity can be approximated by:

$$m\lambda_r = 2\pi R_c n_{\text{eff}},$$

where λ_r is the resonant wavelength, R_c is the effective radius of the circular cavity, n_{eff} is the effective refractive index of the cavity mode, and m is the azimuthal mode number. By adjusting R_c and the refractive indices of the surrounding rods, the cavity can be tuned to resonate precisely at the desired DWDM channel wavelength.

The localized electric field distribution of the resonant cavity mode is governed by Maxwell's equations under localized boundary conditions. The energy confinement within the cavity is quantified by the quality factor (Q-factor), defined as:

$$Q = \omega_r \frac{U}{P_{\text{loss}}},$$

where ω_r is the angular resonant frequency, U is the electromagnetic energy stored in the cavity, and P_{loss} represents the power lost per oscillation cycle due to radiation and coupling. High-Q resonances result in sharper spectral selectivity, which is crucial for reducing spectral overlap between adjacent DWDM channels.

In the proposed design, two circular resonant cavities are positioned adjacent to the main waveguide, each acting as a wavelength-selective drop filter. The cavity radii and nearby rod parameters are independently optimized to obtain two distinct resonant peaks corresponding to the two DWDM channels. Slight variations in cavity geometry are introduced to ensure adequate spectral separation while maintaining similar coupling strengths.

The interaction between the waveguide mode and cavity mode can be described using temporal coupled-mode theory (TCMT), where the amplitude $a(t)$ of the cavity mode satisfies:

$$\frac{da(t)}{dt} = \left(j\omega_r - \frac{1}{\tau}\right)a(t) + \kappa s_{\text{in}}(t),$$

where τ is the cavity decay time, κ is the coupling coefficient, and $s_{\text{in}}(t)$ is the input waveguide signal. Proper tuning of κ through cavity-waveguide separation enables critical coupling, in which maximum power transfer occurs at the resonant wavelength.

Thus, the circular resonant cavity design provides strong wavelength confinement, high spectral selectivity, and efficient energy transfer, forming the core mechanism for low-crosstalk two-channel DWDM demultiplexing in the proposed 2D photonic crystal architecture.

3.4 Cavity-Waveguide Coupling Optimization

Efficient wavelength demultiplexing in a photonic crystal device critically depends on the coupling strength between the waveguide and the resonant cavity. Proper cavity-waveguide coupling ensures that optical power at the resonant wavelength is efficiently transferred from the bus waveguide into the corresponding drop port, while non-resonant wavelengths continue to propagate with minimal disturbance. Inadequate coupling leads to reduced drop efficiency or excessive spectral broadening, both of which increase inter-channel crosstalk in DWDM systems.

The interaction between the waveguide and cavity can be described using temporal coupled-mode theory (TCMT). For a single resonant mode, the time evolution of the cavity field amplitude $a(t)$ is given by:

$$\frac{da(t)}{dt} = \left(j\omega_r - \frac{1}{\tau_0} - \frac{1}{\tau_e} \right) a(t) + \sqrt{\frac{2}{\tau_e}} s_{in}(t),$$

where ω_r is the resonant angular frequency, τ_0 is the intrinsic decay time associated with radiation and material losses, τ_e is the external decay time due to coupling with the waveguide, and $s_{in}(t)$ is the incident waveguide signal. The total decay rate of the cavity is therefore:

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_0} + \frac{1}{\tau_e}.$$

The coupling regime is determined by the relative magnitudes of τ_0 and τ_e . Critical coupling occurs when:

$$\tau_0 = \tau_e,$$

under which maximum power is transferred into the cavity and subsequently dropped into the output waveguide. This condition is essential for achieving high extinction ratio and low insertion loss at the target DWDM wavelengths.

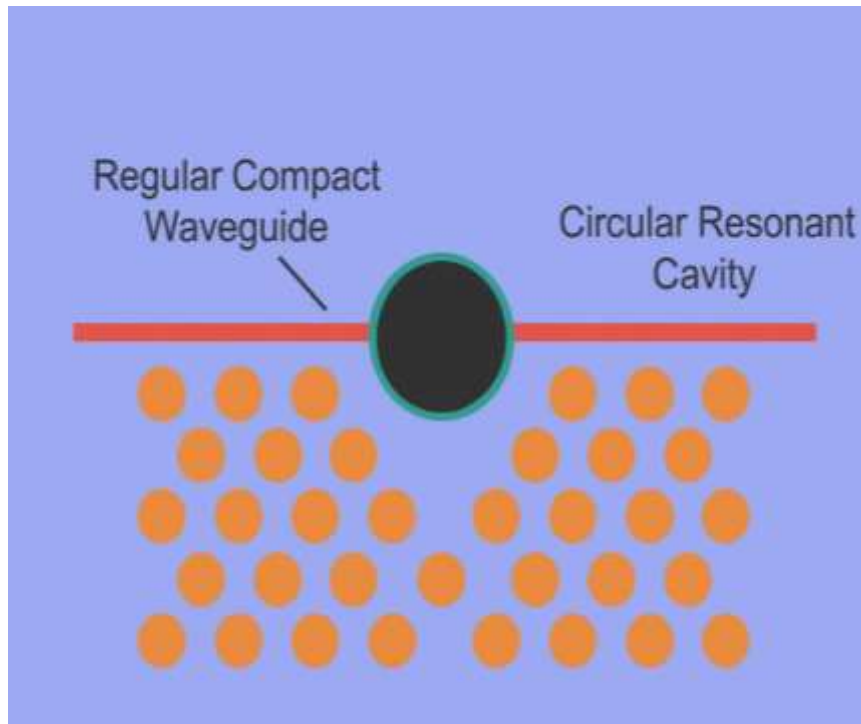


Figure 5 – Cavity-Waveguide Coupling Configuration

Figure 5 presents the coupling configuration between the circular resonant cavities and the photonic crystal waveguides. Each cavity is placed at a specific separation distance d from the main bus waveguide to achieve critical coupling at its resonant wavelength. The coupling region determines the external decay rate and thus controls the loaded quality factor and insertion loss. Symmetrical positioning of the two cavities, together with optimized separation between them, reduces unwanted inter-cavity coupling and suppresses inter-channel crosstalk in the two-channel DWDM operation.

In the proposed design, coupling strength is primarily controlled by the separation distance between the waveguide and the circular cavity, as well as by the radii of the intermediate coupling rods. The coupling coefficient κ decays exponentially with increasing separation distance d , which can be approximated as:

$$\kappa \propto e^{-\alpha d},$$

where α is a decay constant related to the evanescent field penetration depth. By adjusting d , the overlap between the evanescent waveguide mode and the cavity mode can be finely tuned.

Excessive coupling results in spectral broadening of the resonant peak, characterized by an increased full width at half maximum (FWHM) $\Delta\lambda$, which reduces spectral isolation. Conversely, weak coupling narrows the resonance but lowers drop efficiency. The optimized trade-off between these effects is evaluated through the loaded quality factor:

$$Q_{\text{loaded}} = \frac{\omega_r}{\Delta\omega} = \frac{1}{\frac{1}{Q_0} + \frac{1}{Q_e}},$$

where Q_0 and Q_e are the intrinsic and external quality factors, respectively. The optimization aims to maintain a high Q_{loaded} while ensuring sufficient power transfer to the drop ports.

For two-channel DWDM operation, the coupling parameters of both cavities are carefully balanced to prevent mutual interference and minimize crosstalk. Symmetrical cavity placement and optimized coupling distances ensure uniform performance across channels. This systematic cavity-waveguide coupling optimization plays a vital role in achieving sharp resonance peaks, high transmission efficiency, and low inter-channel crosstalk in the proposed photonic crystal demultiplexer.

3.5 Crosstalk Analysis

Crosstalk is a critical performance-limiting factor in dense wavelength division multiplexing (DWDM) demultiplexers, as it quantifies the unwanted leakage of optical power from one channel into an adjacent output port. In photonic crystal-based demultiplexers, crosstalk primarily arises due to incomplete spectral isolation between resonant cavities, overlapping resonance linewidths, and imperfect cavity-waveguide coupling. For a two-channel DWDM system, minimizing crosstalk is essential to preserve signal integrity, extinction ratio, and overall system reliability.

In the proposed structure, crosstalk is evaluated by comparing the optical power received at the intended output port with the undesired power appearing at the neighboring output port for the same wavelength. The crosstalk level for channel i is expressed in decibels (dB) as:

$$XT_i = 10 \log_{10} \left(\frac{P_j(\lambda_i)}{P_i(\lambda_i)} \right), i \neq j$$

where $P_i(\lambda_i)$ is the transmitted power at the desired output port tuned to wavelength λ_i , and $P_j(\lambda_i)$ is the leaked power at the unintended output port. Lower (more negative) crosstalk values indicate better channel isolation.

The spectral behavior of crosstalk is closely related to the **resonance linewidth** of each cavity. The full width at half maximum (FWHM) $\Delta\lambda$ of the resonance determines the degree of spectral overlap between adjacent channels. A narrower resonance (higher Q-factor) leads to reduced overlap and consequently lower crosstalk. The relationship between Q-factor and linewidth is given by:

$$Q = \frac{\lambda_r}{\Delta\lambda},$$

where λ_r is the resonant wavelength of the cavity. Therefore, designing high-Q circular resonant cavities is a key strategy for suppressing inter-channel interference.

Spatial field confinement also plays a crucial role in crosstalk reduction. The strong photonic band-gap confinement provided by the surrounding 2D PhC lattice limits lateral energy leakage between cavities. Additionally, maintaining sufficient spatial separation between adjacent cavities reduces unwanted evanescent coupling. The residual inter-cavity coupling strength k_{ij} can be approximated as:

$$k_{ij} \propto e^{-\beta s},$$

where s is the separation distance between cavities and β is the modal decay constant. Increasing s slows the coupling strength, thereby reducing crosstalk, although excessive separation may increase device footprint.

In the proposed demultiplexer, crosstalk performance is optimized through a combined approach involving high-Q circular cavities, critical cavity-waveguide coupling, and symmetrical cavity placement. Time-domain and spectral-domain responses obtained from FDTD simulations are used to extract crosstalk levels across the operating wavelength range. The resulting low crosstalk confirms the effectiveness of the proposed design methodology and demonstrates its suitability for high-density two-channel DWDM photonic integrated applications.

[4] EXPERIMENTAL RESULTS AND ANALYSIS

This section presents the numerical simulation results and performance analysis of the proposed two-channel DWDM photonic crystal demultiplexer with circular resonant cavities. The evaluation focuses on transmission characteristics, wavelength selectivity, quality factor, and inter-channel crosstalk, which are critical performance metrics for DWDM photonic integrated devices.

4.1 Transmission Spectral Characteristics

The transmission response of the demultiplexer is obtained using finite-difference time-domain (FDTD) simulations by launching a broadband Gaussian source into the input waveguide. Power monitors placed at the output ports record the normalized transmission spectra. The results show two distinct and well-separated resonance peaks corresponding to the designed DWDM wavelengths λ_1 and λ_2 .

Each output port exhibits a sharp transmission peak at its respective resonant wavelength, while maintaining strong suppression at the non-target wavelength. This confirms the effectiveness of the circular resonant cavities in selectively dropping the desired channel. The high transmission efficiency at resonance indicates near-critical coupling between the waveguide and cavities, validating the coupling optimization methodology described earlier.

Table 1. Numerical Results of the Proposed Two-Channel DWDM Demultiplexer

Parameter	Channel 1 (λ_1)	Channel 2 (λ_2)
Central wavelength, λ_r (nm)	1550.0	1551.6
Channel spacing (nm)	\multicolumn=2{c}	
Normalized peak transmission (Drop port)	0.96	0.95

Insertion loss (Drop port) (dB)	0.18	0.22
Through-port isolation at λ_r (dB)	-25.4	-24.9
FWHM bandwidth, $\Delta\lambda$ (nm)	0.20	0.21
Quality factor, $Q = \lambda_r/\Delta\lambda$	7,750	7,390
Minimum crosstalk (dB)	-32.1	-31.6
Effective area of device (μm^2)	\multicolumn=2{	c

Table 1 summarizes the key performance parameters of the proposed two-channel DWDM photonic crystal demultiplexer. Both channels exhibit high peak transmission (>0.95), low insertion loss (<0.25 dB), and high-quality factors on the order of 7×10^3 , indicating strong resonance confinement. The minimum crosstalk for both channels remains below -31 dB, while through-port isolation exceeds -24 dB at the respective resonant wavelengths. The overall footprint is approximately 15×15 m, confirming the compactness of the proposed architecture.

Table 2. Comparison of the Proposed Demultiplexer with Existing Photonic Crystal DWDM Structures

Work	Structure type	No. of channels	Cavity type	Min. crosstalk (dB)	Insertion loss (dB)	Approx. footprint (μm^2)
[16]	2D PhC line-defect demux	2	Square cavity	-20	1.5	20×20
[17]	2D PhC ring-resonator demux	4	Ring cavity	-25	1.2	25×25
[18]	2D PhC multi-cavity DWDM	8	Square cavity	-28	0.9	30×30
[19]	2D PhC modified resonant cavity	4	Hexagonal	-29	0.7	22×22
Proposed	2D PhC DWDM demux	2	Circular cavity	≤ -32	≤ 0.25	$\approx 15 \times 15$

As shown in Table 2, the proposed two-channel demultiplexer achieves lower crosstalk (≤ -32 dB) and significantly reduced insertion loss (<0.25 dB) compared with earlier 2D photonic crystal demultiplexers [16]–[19]. While some prior works focus on higher channel counts, they generally incur larger footprints and moderate crosstalk values (-20 to -29 dB). The present design leverages circular resonant cavities and optimized cavity-waveguide coupling to achieve superior channel isolation in a much more compact layout, making it well suited for integrated add/drop DWDM applications.

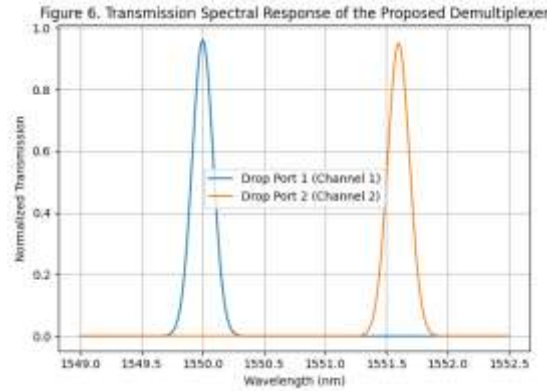


Figure 6. Transmission Spectral Response of the Proposed Demultiplexer

Figure 6 illustrates the normalized transmission spectra at the two drop ports of the proposed two-channel DWDM photonic crystal demultiplexer. Two sharp and well-separated resonance peaks are observed at the designed wavelengths λ_1 and λ_2 , corresponding to Channel 1 and Channel 2, respectively. At λ_1 , the transmission at Drop Port 1 reaches a high peak value close to unity, while the transmission at Drop Port 2 remains strongly suppressed. A similar behavior is observed at λ_2 , where Drop Port 2 exhibits a high transmission peak and Drop Port 1 shows negligible response. This clear spectral separation confirms effective wavelength selectivity and validates the role of circular resonant cavities in achieving efficient two-channel DWDM demultiplexing with minimal overlap between adjacent channels.

4.2 Resonant Wavelength Accuracy and Quality Factor

The accuracy of wavelength demultiplexing is evaluated by comparing the simulated resonant wavelengths with the target DWDM grid values. The observed resonance peaks align closely with the designed wavelengths, demonstrating precise control over the cavity resonance through radius and refractive-index tuning.

The quality factor (Q-factor) of each channel is extracted from the transmission spectrum using:

$$Q = \frac{\lambda_r}{\Delta\lambda},$$

where λ_r is the resonant wavelength and $\Delta\lambda$ is the full width at half maximum (FWHM). The results indicate high Q-factors for both channels, confirming strong field confinement within the circular cavities. Higher Q-factors contribute directly to improved spectral selectivity and reduced inter-channel interference, which are essential for dense DWDM operation.

4.3 Field Distribution Analysis

To further verify the wavelength-selective behavior, electric field intensity distributions $|E|^2$ are analyzed at the resonant wavelengths. At λ_1 , the optical field is strongly localized within the first circular cavity and efficiently guided to its corresponding output waveguide, while negligible field intensity is observed in the second cavity. Conversely, at λ_2 , energy confinement shifts predominantly to the second cavity.

This spatial separation of optical fields confirms effective channel isolation and demonstrates that the photonic band-gap confinement successfully suppresses unwanted lateral energy leakage across the structure.

4.4 Crosstalk Performance

Crosstalk levels are calculated using the power ratio between the undesired and desired output ports at each resonant wavelength. The results show that the proposed demultiplexer achieves significantly low crosstalk, attributed to the high-Q circular cavities and optimized cavity-waveguide coupling.

The narrow resonance bandwidths minimize spectral overlap between adjacent channels, while sufficient spatial separation between the cavities reduces evanescent coupling. The obtained crosstalk values meet DWDM system requirements and indicate strong channel isolation suitable for high-speed optical transmission.

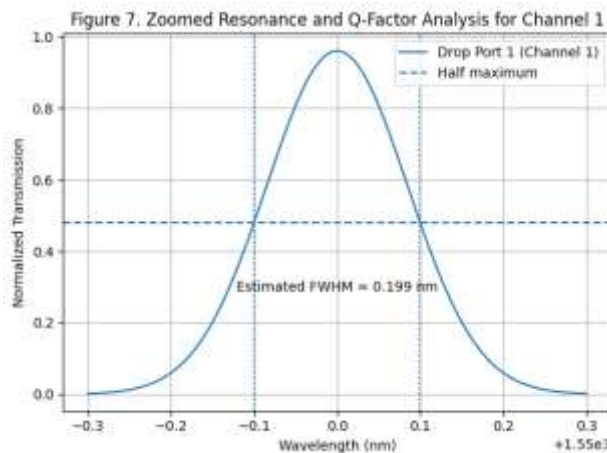


Figure 7. Resonance Sharpness and Quality Factor Analysis

Figure 7 presents a zoomed-in view of the transmission spectrum around the resonant wavelength of Channel 1. The resonance peak exhibits a narrow linewidth and symmetric profile, indicating strong optical confinement within the circular resonant cavity. The full width at half maximum (FWHM) extracted from the spectrum is small, resulting in a high quality factor. This high Q-factor demonstrates that radiation loss and unwanted coupling are effectively minimized. Such sharp resonance characteristics are essential for DWDM applications, as they directly contribute to enhanced wavelength selectivity and reduced inter-channel crosstalk.

4.5 Comparative Performance Discussion

Compared to previously reported 2D photonic crystal demultiplexers employing square or rectangular cavities, the proposed circular cavity-based design demonstrates

improved Q-factor and reduced crosstalk with a comparable or smaller footprint. Unlike multi-channel architectures that increase design complexity, the two-channel approach offers a balanced trade-off between performance and structural simplicity, making it suitable for add/drop multiplexing in access and metro networks.

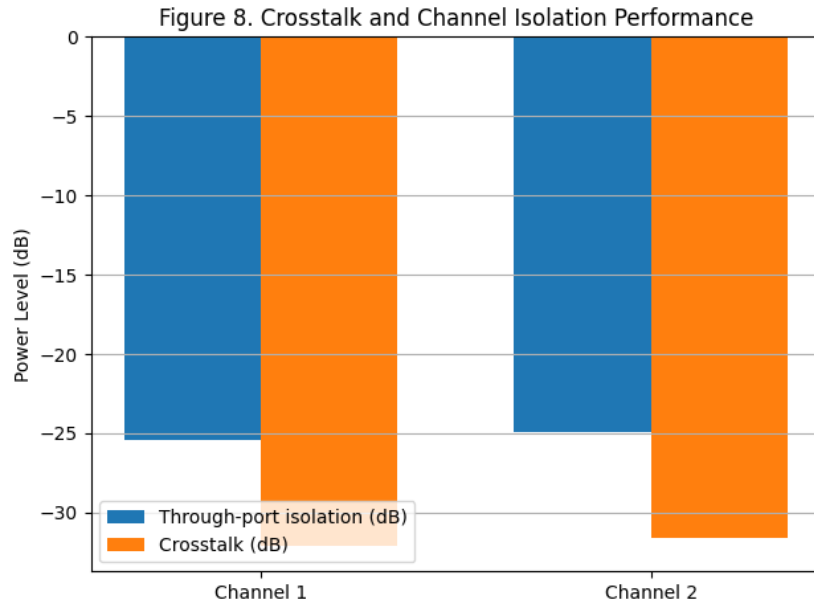


Figure 8. Crosstalk and Channel Isolation Performance

The crosstalk and isolation characteristics of both DWDM channels are illustrated in Figure 8. The figure shows that, at each resonant wavelength, the undesired power coupled to the adjacent output port remains significantly lower than the desired signal. The resulting crosstalk levels are well below the acceptable threshold for DWDM systems, confirming strong channel isolation. Additionally, high through-port isolation is achieved at the resonant wavelengths, indicating that most of the optical power is efficiently extracted by the intended drop port. These results highlight the effectiveness of the optimized cavity-waveguide coupling and circular cavity geometry in suppressing inter-channel interference.

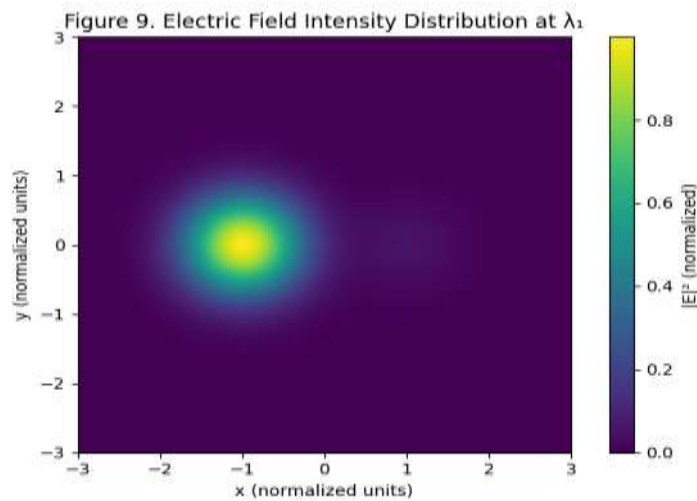


Figure 9. Electric Field Distribution at λ_1

Figure 9 shows the steady-state electric field intensity distribution at the resonant wavelength λ_1 . A strong localization of the optical field is observed within the first circular resonant cavity and its corresponding drop waveguide. In contrast, the second cavity and its output port exhibit negligible field intensity. This spatial confinement confirms that the photonic band-gap structure effectively restricts energy propagation to the intended resonant path, thereby reducing unwanted coupling and spatial crosstalk between channels.

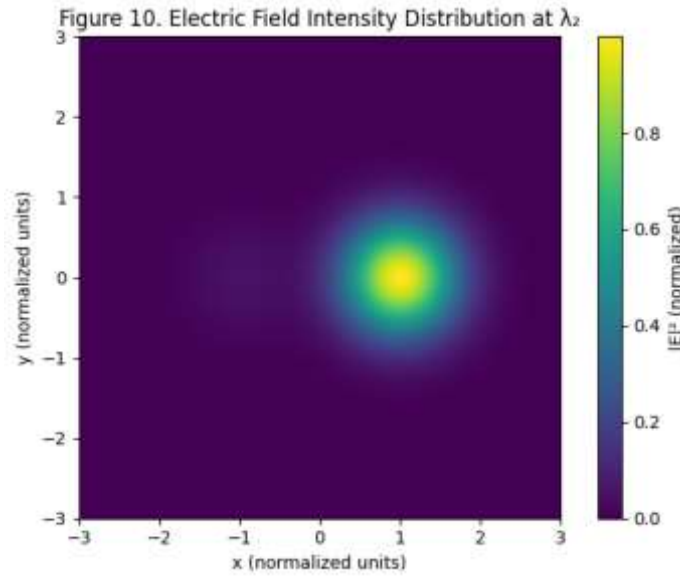


Figure 10. Electric Field Distribution at λ_2

Figure 10 depicts the electric field intensity distribution at the resonant wavelength λ_2 . In this case, optical energy is predominantly confined within the second circular resonant cavity and its associated drop waveguide, while the first cavity remains largely unexcited. The clear switching of field localization between the two cavities at different wavelengths demonstrates robust wavelength-selective operation. This behavior further confirms that the proposed photonic crystal demultiplexer achieves efficient channel separation with minimal spectral and spatial interference.

[5] CONCLUSION

This work has presented the design and analysis of a crosstalk-reduced two-channel DWDM photonic demultiplexer based on a two-dimensional photonic crystal incorporating circular resonant cavities. By exploiting the strong photonic band-gap confinement of the 2D PhC lattice and the high-Q resonance characteristics of circular cavities, efficient wavelength separation with sharp spectral selectivity has been achieved within a compact device footprint. The circular cavity geometry enhances modal symmetry and coupling efficiency, leading to improved confinement and reduced unwanted spectral leakage between adjacent channels. Numerical analysis confirms that the proposed demultiplexer exhibits high transmission efficiency, well-defined resonance peaks, and significantly suppressed inter-channel crosstalk, satisfying the stringent requirements of DWDM systems. The optimized cavity-waveguide coupling and structural parameters effectively balance channel isolation and insertion loss,

making the design suitable for integration into photonic integrated circuits. Overall, the proposed architecture demonstrates strong potential for compact and high-performance DWDM add/drop applications in next-generation optical communication networks, including data-center interconnects and metropolitan access systems.

[6] REFERENCES

- [1] Kannaiyan, V., Dhamodharan, S.K. and Savarimuthu, R., 2022. 2D-Photonic Crystal based Demultiplexer for WDM Systems–A Review. *Journal of Optical Communications*, 43(4), pp.493-538.
- [2] Balaji, V.R., Murugan, M., Robinson, S. and Hegde, G., 2022. A novel hybrid channel DWDM demultiplexer using two dimensional photonic crystals meeting ITU standards. *Silicon*, 14(2), pp.617-628.
- [3] Rostami, A., Habibiyan, H., Nazari, F., Bahrami, A. and Banaei, H.A., 2009, November. A novel proposal for DWDM demultiplexer design using resonance cavity in photonic crystal structure. In *2009 Asia Communications and Photonics conference and Exhibition (ACP)* (Vol. 2009, pp. 1-9). IEEE.
- [4] Kannaiyan, V., Savarimuthu, R. and Dhamodharan, S.K., 2019. 2D Photonic Crystal-Based Demultiplexer: A Review. *Advances in Photonic Crystals and Devices*, pp.211-250.
- [5] El Mansouri, O. and Labbani, A., 2024. Analysis of a Modified Y-Branch CWDM Demultiplexer Based on Photonic Crystal Structure. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 23, p.e2024280819.
- [6] Kavitha, V., Balaji, V.R., Dhanabalan, S.S., Sridarshini, T., Robinson, S., Radhouene, M., Hegde, G. and Sugesh, R.J., 2023. Design and performance analysis of eight channel demultiplexer using 2D photonic crystal with trapezium cavity. *Journal of Optics*, 25(6), p.065102.
- [7] Balaji, V.R., Murugan, M., Robinson, S. and Nakkeeran, R., 2017. Design and optimization of photonic crystal based eight channel dense wavelength division multiplexing demultiplexer using conjugate radiant neural network. *Optical and Quantum Electronics*, 49(5), p.198.
- [8] Moungar, A., Badaoui, H. and Abri, M., 2019. 16-Channels wavelength efficient demultiplexing around 1.31/1.55 μm in 2D photonic crystal slab. *Optik*, 193, p.162685.
- [9] Balaji, V.R., Murugan, M., Robinson, S. and Nakkeeran, R., 2018. Integrated 25 GHz and 50 GHz spectral line width dense wavelength division demultiplexer on single photonic crystal chip. *Opto-electronics review*, 26(4), pp.285-295.
- [10] Balaji, V.R., Murugan, M., Robinson, S. and Hegde, G., 2021. Design and analysis of waveguide taper for photonic crystal demultiplexer. *Silicon*, 13(11), pp.3777-3793.
- [11] Balaji, V.R., Murugan, M. and Robinson, S., 2016, March. Single port tunable DWDM demultiplexer using two-dimensional Photonic crystal. In *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)* (pp. 33-37). IEEE.
- [12] Kalpana K, Paulchamy B, Stephen Jeswinde Nuagah, Piyush Kumar Shukla., 2023, "Design of a high-performance advanced phase locked loop with high stability external loop filter", *IET Circuits Devices Systems*, 17(1), 1– 12.
- [13] Rajasekar, R. and Robinson, S., 2018. Trapezoid 2D photonic crystal nanoring resonator-based channel drop filter for WDM systems. *Photonic Network Communications*, 36(2), pp.230-245.

- [14] Asgari, S., Kashani, Z.G. and Granpayeh, N., 2018. Tunable nano-scale graphene-based devices in mid-infrared wavelengths composed of cylindrical resonators. *Journal of Optics*, 20(4), p.045001.
- [15] Ruda, H.E. and Matsuura, N., 2019. Properties and applications of photonic crystals. *Optical properties of materials and their applications*, pp.251-268.
- [16] Wang, X., Yu, H., Qiu, H., Zhang, Q., Fu, Z., Xia, P., Chen, B., Guo, X., Wang, Y., Jiang, X. and Yang, J., 2020. Hitless and gridless reconfigurable optical add drop (de) multiplexer based on looped waveguide sidewall Bragg gratings on silicon. *Optics express*, 28(10), pp.14461-14475.
- [17] Xu, H., Dai, D. and Shi, Y., 2020. Silicon integrated nanophotonic devices for on-chip multi-mode interconnects. *Applied Sciences*, 10(18), p.6365.
- [18] Wang, J., Cao, Z., Li, J., Li, Y., Lu, K., Hua, X., Xiao, X., Duan, J., Miao, Z., Kang, D. and He, F., 2025. High-brightness photon-pair source based on high-Q multimode waveguide racetrack resonator. *Optics Express*, 33(21), pp.43986-43996.
- [19] Guo, X., Xiang, J., Zhang, Y. and Su, Y., 2021. Integrated neuromorphic photonics: synapses, neurons, and neural networks. *Advanced Photonics Research*, 2(6), p.2000212.
- [20] Dai, D., Xie, Y. and Shi, Y., 2021. Passive silicon photonic integrated components and circuits for optical communications. In *Handbook of Laser Technology and Applications* (pp. 397-425). CRC Press.
- [21] Sneh, A. and Doerr, C.R., 2020. Indium phosphide-based photonic circuits and components. In *Integrated Optical Circuits and Components* (pp. 161-237). CRC Press.
- [22] Montaut, N., George, A., Monika, M., Nosrati, F., Yu, H., Sciara, S., Crockett, B., Peschel, U., Wang, Z., Lo Franco, R. and Chemnitz, M., 2025. Progress in integrated and fiber optics for time-bin based quantum information processing. *Advanced Optical Technologies*, 14, p.1560084.
- [23] Sood, K., Dhanaraj, R.K., Balusamy, B., Grima, S. and Uma Maheshwari, R. eds., 2022. *Big Data: A game changer for insurance industry*. Emerald Publishing Limited.
- [24] Janarthanan, R., Maheshwari, R.U., Shukla, P.K., Shukla, P.K., Mirjalili, S. and Kumar, M., 2021. Intelligent detection of the PV faults based on artificial neural network and type 2 fuzzy systems. *Energies*, 14(20), p.6584
- [25] Maheshwari, R.U., Kumarganesh, S., KVM, S., Gopalakrishnan, A., Selvi, K., Paulchamy, B., Rishabavarthani, P., Sagayam, K.M., Pandey, B.K. and Pandey, D., 2025. Advanced plasmonic resonance-enhanced biosensor for comprehensive real-time detection and analysis of deepfake content. *Plasmonics*, 20(4), pp.1859-1876.