

Dual-band filtering-beam splitting integrated device based on photonic crystals for wavelength-division multiplexing systems

Z. M. HUANG, Z. H. WU*, Y. F. CHI, J. T. LI, M. ZHONG, Y. QIU, B. TANG

School of Sciences, Southwest Petroleum University, 610500, Chengdu, China

As optical communications demand greater bandwidth and efficiency, we propose a compact dual-band photonic-crystal device with a triangular lattice that integrates a ring resonator with point-defect microcavities to perform simultaneous filtering and symmetric 1:1 beam splitting at 1.31 μm and 1.55 μm . FDTD results show total transmittances of 96.4% and 98.6%, filtering efficiencies of 99.63% and 99.12%, insertion loss as low as 0.015 dB, and Q-factors of 689 and 738, demonstrating strong spectral selectivity and negligible loss. This highly integrated, low-loss, high-Q design is promising for compact WDM photonic integrated circuits.

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1. Introduction

Photonic crystals (PCs), conceptualized by E. Yablonovitch [1] and S. John [2] in 1987, consist of artificial periodic dielectric structures exhibiting distinct permittivity values [3]. Decades of progress in photonics have driven the development of integrated photonic devices, including those based on PCs. As periodic materials, PCs possess unique properties such as photonic bandgaps (PBGs) [4], photon localization [5], negative refraction [6], and self-collimation [7]. The PBG enables control over the light propagation direction and wavelength, prohibiting specific wavelengths from propagating within the crystal [8]. Localization facilitates the creation of guided-mode defect states within the PBG when defects are introduced (e.g., by altering the radius of dielectric rods or refractive index), which confines light at the defect site while blocking other wavelengths within the gap [9]. Leveraging these properties, diverse PC devices have been designed, including filters [10], beam splitters [11], optical switches [12], optical multiplexer and demultiplexer [13], and optical fibers [14]. Among these, PC beam splitters and filters represent significant research areas.

Optical beam splitters are essential in optical communication, as they control the power distribution and path switching of light waves. Light propagation through defects in photonic crystals exhibits lower and more controllable loss, giving photonic crystal beam splitters distinctive advantages in communication systems [15]. Jin Rui [16] designed an ultra-wideband 1×3 beam splitter based on a two-dimensional photonic crystal waveguide.

Different splitting ratios can be achieved by optimizing the radii and offsets of six control dielectric rods. Yang Cao [17] proposes a polarization-insensitive 1×5 power splitter based on photonic crystals, which employs the particle swarm optimization algorithm for inverse design of air hole radius and position control. By introducing controlled air holes at the waveguide junction, thus the device achieves both equal and unequal distribution of high-transmission optical beams.

As a frequency-selective device, the core function of an optical filter is to allow specific wavelengths to pass while blocking others, and it is also a very important device in the field of optical communication. Compared with traditional filters, photonic crystal filters have better filtering effects, less interference, and are more conducive to ensuring the complete transmission of signals [18]. DIVYA et al. [19] designed a ring resonator-based channel drop filter for coarse wavelength division multiplexers. By modifying the inner rod radius enabled selective output at 1.524 μm , 1.544 μm , and 1.565 μm , they achieved transmittances of 88%, 76%, and 72% with quality factors of 381, 386, and 391.2, respectively. PUJA et al. [20] designed an all-optical add-drop filter using a square ring resonator, analyzing the impact of lattice constant, refractive index, and rod radius on performance to achieve high efficiency and quality factor.

While substantial research exists on individual beam splitters or filters, integrated devices combining both functions are less explored. Qian Yiting et al. [21] designed a device with dual filtering and splitting functions, but its structure was merely a combination of separate components within the same 2D photonic crystal,

resulting in low integration. Wu Cong et al. [22] designed a ring-cavity-based dual-channel filtering beam splitter, yet its performance (with a filtering efficiency of 70% and a splitting transmittance of 79.70%) requires optimization. Therefore, to address these limitations, this paper integrates the principles of ring resonator filters and beam splitters to design a compact four-channel filtering beam splitter within a single 2D photonic crystal structure. Leveraging the plane wave expansion method (PWE) and finite-difference time-domain (FDTD) method, the device's filtering and beam-splitting performance is verified and analyzed.

2. Numerical simulation and analysis

2.1. Analytical method

The transmission characteristics and performance of the designed 2D PC device were analyzed primarily using the plane wave expansion method (PWE) [23] and the finite-difference time-domain (FDTD) method [24].

The PWE method is a computational approach fundamentally derived from Maxwell's equations. It leverages the periodicity of the dielectric function of photonic crystals by expanding the electromagnetic field and the dielectric function into Fourier series in their respective primitive lattice space and reciprocal lattice space. By applying Bloch's theorem, the electromagnetic field is expressed in a plane wave form. A specific number of plane wave basis sets are selected, substituted into Maxwell's equations to construct a matrix equation, and subsequently solved as an eigenvalue problem to determine the bandgap structure of the photonic crystal.

For FDTD analysis of PCs, the periodic dielectric structure is discretized. Maxwell's equations are used to model the electromagnetic field. Continuous differential equations are transformed into difference equations via discrete differentiation in time and space. Combined with boundary and initial conditions, iterative methods calculate the electric and magnetic field components at each time step and spatial grid point, simulating light wave propagation within the PC.

2.2. Performance indicators of the filter beam splitter

The performance of a multi-output port filtering beam splitter is typically characterized by transmittance (T), quality factor (Q), and insertion loss (IL) [25].

Transmittance is defined as the ratio of the optical power at a designated output port to the incident optical power. It is calculated using equation (1):

$$T = P_{\text{out}} / P_{\text{in}} \times 100\% \quad (1)$$

where P_{out} denotes the output power at the target port, and P_{in} is the input power.

Quality factor reflects the spectral resolution of the filter. A higher Q value indicates stronger frequency selectivity at a specific wavelength and improved light localization capability. It is calculated as equation (2):

$$Q = \lambda_0 / \Delta\lambda \quad (2)$$

where λ_0 is the central wavelength of the filtered signal, and $\Delta\lambda = \lambda_2 - \lambda_1$ is the full width at half maximum (FWHM), with λ_1 and λ_2 representing the two wavelengths at half-maximum power.

Insertion loss, measured in dB, quantifies the transmission loss of the device. Lower IL values correspond to better filtering performance. It is calculated as equation (3):

$$IL = -10\lg(P_{\text{out}}/P_{\text{in}}) \quad (3)$$

where P_{out} is the optical power at the output port, and P_{in} is the optical power at the input port.

2.3. Structure

The designed device is based on a two-dimensional triangular-lattice photonic crystal composed of 19×20 silicon dielectric rods arranged periodically in an air background, with its specific structure illustrated in Fig. 1(a). The lattice constant is set to $0.65 \mu\text{m}$, and the background medium is air, resulting in a background refractive index of 1. The circular dielectric rods possess a refractive index of 3.6 and a radius of $0.08 \mu\text{m}$. The Brillouin zone of the unit cell is depicted in Fig. 1(a).

The band structure of this configuration under TE polarization was analyzed using the plane wave expansion method, with the results shown in Fig. 1(b). The horizontal axis corresponds to the wavevector path $\Gamma\text{--M--K--}\Gamma$ in Fig. 1(b), while the vertical axis represents the normalized frequency, with the photonic band gap region indicated by the shaded area. The result reveals a significantly wider photonic band gap within this structure. The normalized frequency range of the band gap spans from 0.354 to 0.552 $\omega a/2\pi c$ (where ω is the angular frequency, a is the lattice constant, and c is the speed of light in vacuum). Based on the normalized frequency formula, the corresponding operational wavelength ranges for this structure can be calculated as $1.177 \mu\text{m}$ to $1.836 \mu\text{m}$.

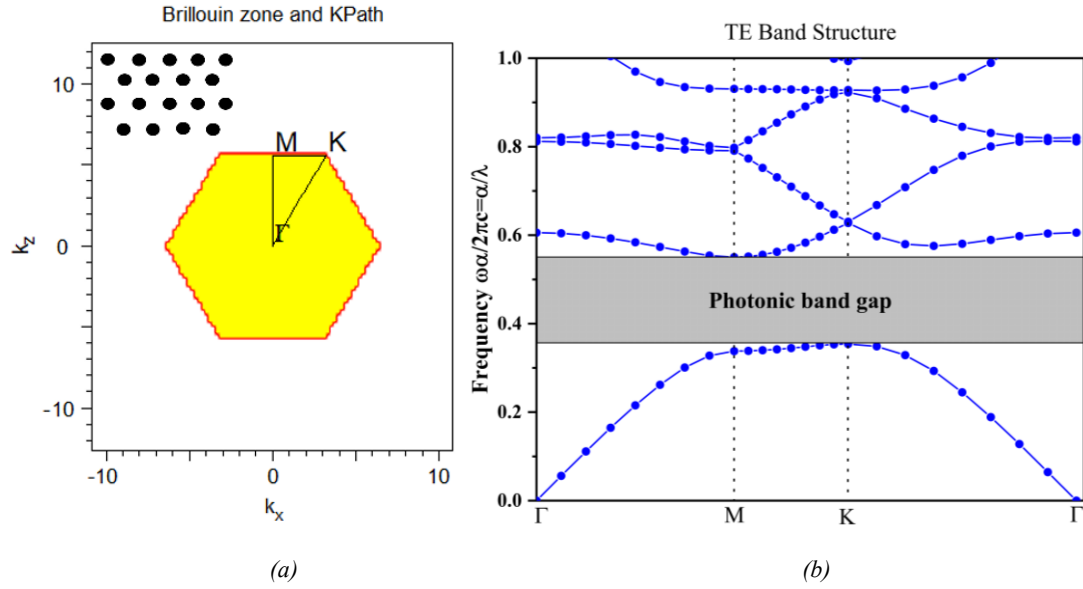


Fig. 1. The first Brillouin zone of the unit cell and a partial structure of the photonic crystal are shown in (a). The photonic band gap for TE polarization is indicated in (b), spanning the normalized frequency range from 0.354 to 0.552 $\omega a/2\pi c$ (colour online)

To integrate both beam splitting and filtering functionalities within a single photonic crystal device, this work proposes a novel two-dimensional photonic crystal filter-splitter with a new structure, as illustrated

in Fig. 2. The device comprises three functional components: an input channel, a ring resonator cavity, and an output channel system.

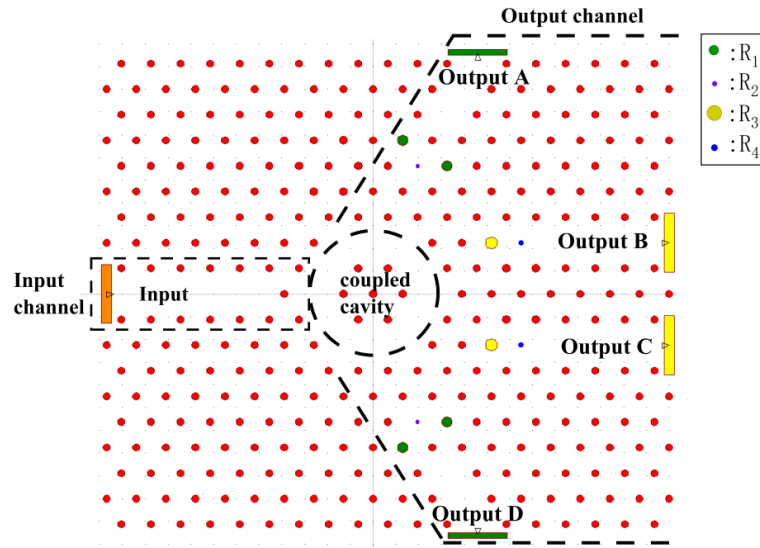


Fig. 2. The device architecture comprises three functional sections: an input channel, a coupling cavity, and an output channel (colour online)

The input channel incorporates a linear defect waveguide. It is terminated with a dielectric isolation column (radius = 0.080 μm) to prevent broadband transmission into the resonator.

Due to the multimode nature and optical selectivity of ring resonators [26], which can support the simultaneous existence and oscillation of multiple optical modes while

allowing only light waves with specific frequencies to satisfy the resonance conditions, this structure enables the first-stage resonant filtering of light waves. The ring resonator structure is shown in Fig. 3(a). It is formed by removing 12 dielectric rods located at distances of $2a$ and $1.732a$ from the central circular dielectric rod in a complete photonic crystal, thereby creating a ring

resonator with 7 dielectric rods at the center. The radius of the central dielectric rod is $1.07r$. When the finite-difference time-domain (FDTD) method was used to scan the operating wavelengths of the ring resonator,

the results demonstrated that the resonator allows only three specific wavelengths to propagate: $1.310\ \mu\text{m}$, $1.440\ \mu\text{m}$, and $1.550\ \mu\text{m}$. The scan results are illustrated in Fig. 3(b).

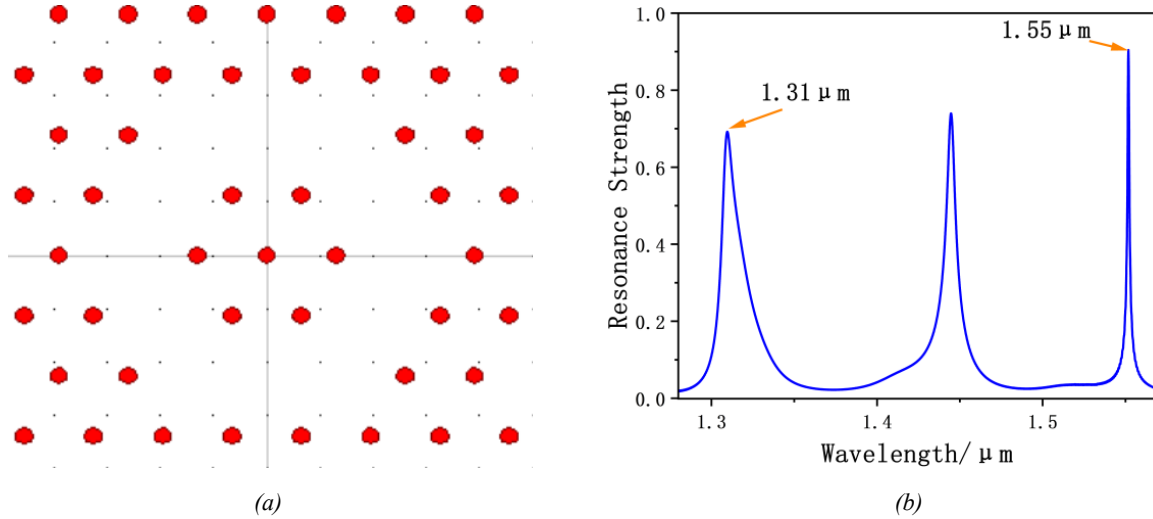


Fig. 3. The ring resonator coupling cavity is depicted in (a), with its resonant frequency shown in (b) (colour online)

The output system comprises four ports (A, B, C, and D), each incorporating specialized microcavity designs that enable dual-wavelength selective filtering through secondary resonant coupling and symmetric equal-ratio power splitting. Ports A and D feature microcavities consisting of a coupling rod and an intracavity rod with radii of $0.32r$ and $1.42r$ ($r = 0.080\ \mu\text{m}$), respectively, while ports B and C utilize microcavities composed of a coupling rod and an output rod with radii of $1.63r$ and $0.55r$. This symmetrical architecture simultaneously facilitates wavelength-specific filtering at ports A and D and balanced power division between the two port pairs.

2.4. Analysis of simulation result

The simulation experiment was performed using the FDTD method. A continuous-wave (CW) optical signal, covering a wavelength range of $1.20\ \mu\text{m}$ to $1.70\ \mu\text{m}$, was introduced through the Input port. A monitor was positioned at the Output port to record transmission

characteristics. The overall simulated performance of the device, illustrated in Figs. 4(a) and (b), demonstrates successful integration of filtering and power-splitting functionalities for both $1.31\ \mu\text{m}$ and $1.55\ \mu\text{m}$ optical waves. For the $1.310\ \mu\text{m}$ incident light, the input propagates through the ring resonator, undergoing primary coupling, followed by secondary coupling in the cavities associated with output ports B and C, resulting in symmetric channel outputs. Output ports A and D exhibit 0% transmittance, while ports B and C each achieve 48.2% transmittance, which results in a total transmittance of 96.4%. Similarly, for the $1.550\ \mu\text{m}$ incident light, output ports B and C show 0% transmittance, whereas ports A and D each attain 49.3% transmittance, corresponding to a total transmittance of 98.6%. The transmittance spectra for these wavelengths are explicitly detailed in Figs. 5(a) and (b), respectively. These results confirm robust power-splitting with high efficiency and wavelength-selective routing.

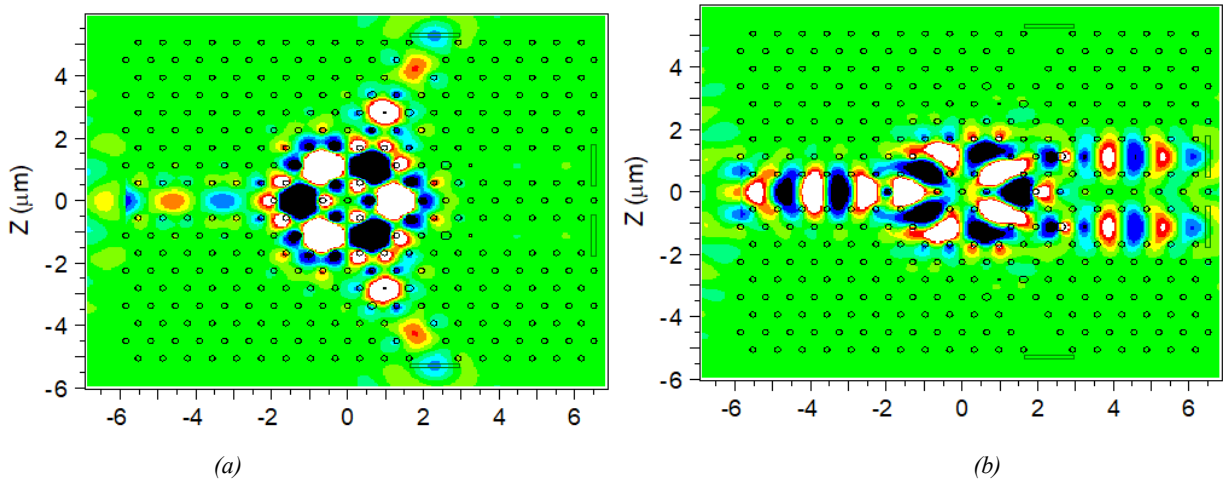


Fig. 4. The field distributions of the device under incident wavelengths of (a) 1.31 μm and (b) 1.55 μm , respectively (colour online)

The device operates via dual-wavelength-dependent resonant coupling within the ring cavity. At 1.31 μm , light is confined and redistributed to ports B and C; at 1.55 μm , it is directed to ports A and D via resonant coupling. The near-zero transmittance in non-resonant ports and high total transmittance values of 96.4% and 98.6% are shown in Fig. 5. They indicate minimal insertion loss and efficient power division. The symmetric port performance

demonstrates precise control over coupling mechanisms and structural design. These findings align with theoretical predictions and validate the device's potential for wavelength-division multiplexing (WDM) and integrated photonic circuits requiring simultaneous filtering and splitting. The consistency between simulation and expectation reinforces the reliability of the FDTD method and the design's scalability.

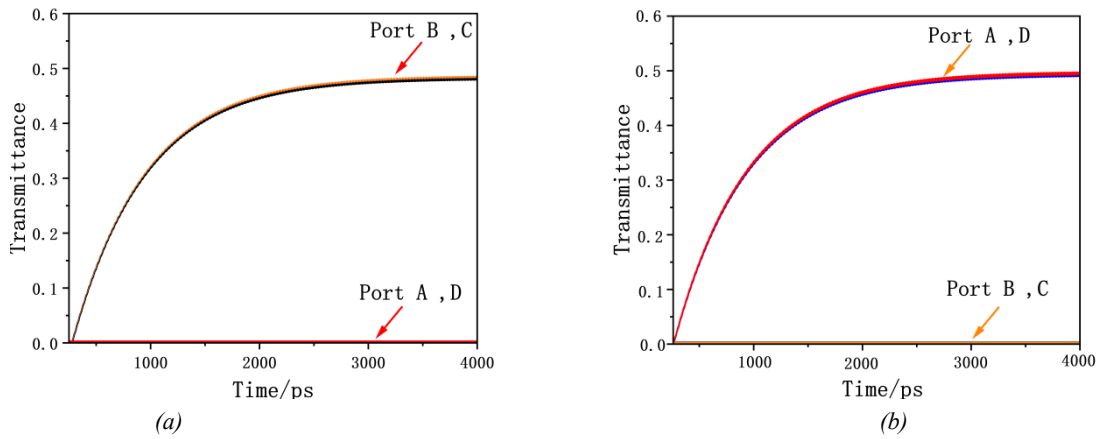


Fig. 5. The transmittance at ports A, B, C, and D under incident wavelengths of (a) 1.31 μm and (b) 1.55 μm , respectively (colour online)

As shown in Fig. 6, the filtering efficiency for 1.31 μm and 1.55 μm illumination reaches 99.63% and 99.12%, respectively, demonstrating near-unity spectral selectivity at both target wavelengths. Corresponding quality factors

(Q) and insertion loss values are quantified in Table 1. The maximum IL across all output channels is only 0.02 dB, accompanied by exceptionally high Q factors of 689 and 738, confirming outstanding filtering performance.

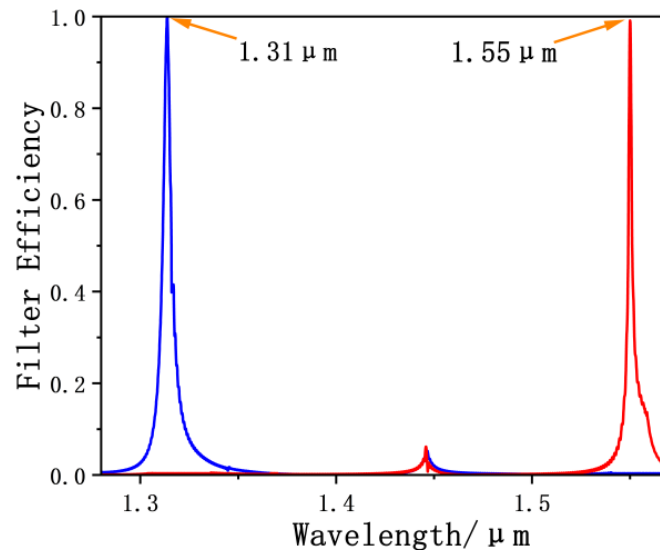


Fig. 6. The filtering efficiency of the device at the operating wavelengths of 1.31 μm and 1.55 μm (colour online)

Table 1. Quality factor and insertion loss for resonant wavelength

Resonant Wavelength (μm)	Quality factor	Insertion Loss (dB)
1.310	689	0.02
1.550	738	0.015

Collectively, the simulations verify that the proposed PC structure simultaneously achieves efficient wavelength filtering and beam splitting while maintaining exceptional performance metrics essential for advanced integrated photonic systems.

2.5. Discussion

By leveraging the resonant properties of ring resonators and point-defect microcavities, this study proposes a PC device capable of simultaneous wavelength filtering and beam splitting, with its functional feasibility validated by electromagnetic simulations. Comparative

performance metrics against prior works—including operational wavelengths, port count, transmission efficiency, filtering efficiency, quality factors (Q), and insertion loss—are quantified in Table 2. The designed device uniquely targets 1.31 μm and 1.55 μm wavelengths, which represent optimal low-loss transmission windows for medium-haul and long-haul optical communications due to minimized scattering impairments. Crucially, it demonstrates superior performance: relative to referenced devices, it achieves an 8.16% and 17.76% higher average transmission, a 5.53% and 17.69% greater filtering efficiency, a 196.5-unit higher average Q-factor, and a 0.0175 dB lower average insertion loss.

Table 2. Comparison of filtering beam splitter

YEAR [Ref.]	Working Wavelength (μm)	Number of ports	Transmissivity (%)	Filter Efficiency (%)	Quality Factor (Q)	Insertion Loss (dB)
2025[27]	1.437/ 1.642	4	96.32/ 82.36	99.5/ 88.2	513/ 521	0.02/ 0.55
2025[28]	1.527/ 1.550	3	66.72/ 92.76	70.62/ 92.76	-	-
This work	1.310/ 1.550	4	96.4/ 98.6	99.63/ 99.12	689/ 738	0.02/ 0.015

3. Conclusion

This study proposes a novel two-dimensional photonic crystal integrated filtering and beam-splitting device that seamlessly combines the functions of conventional photonic crystal filters and splitters within a single compact structure. By optimizing the ring-coupled resonator, coupled microcavities, and intracavity dielectric configuration, the device simultaneously achieves beam splitting and wavelength-selective filtering, demonstrating a high degree of multifunctional integration. Simulation results show that at 1.31 μm , the filtering efficiency reaches 99.63% with a total transmittance of 96.4%, while at 1.55 μm , the values reach 99.12% and 98.6%, respectively. The four-channel device exhibits extremely low insertion loss (≤ 0.04 dB) and exceptionally high-quality factors, up to 738. Compared with previously reported multifunctional designs, which typically suffer from separated structures, low integration, and reduced filtering and splitting efficiencies, the proposed design achieves superior performance in a compact monolithic configuration—featuring significantly enhanced transmittance, filtering efficiency, and Q-factor, along with substantially reduced insertion loss. Furthermore, the proposed design concept can be extended to multi-channel or broadband photonic devices, offering promising potential for future all-optical communication systems and high-density photonic integrated circuits.

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*Corresponding author: wuzhenhai@swpu.edu.cn