

High-Q Narrowband Optical Filter on Silicon-on-Insulator Platform Using Perturbed Sinusoidal Bragg Grating

Hamed Saghaei, *Member, IEEE*, and Kambiz Moez, *Senior Member, IEEE*

Abstract—In this paper, we report the design, fabrication, and experimental characterization of a high-Q narrowband optical filter implemented on a silicon-on-insulator (SOI) platform using perturbed sinusoidal Bragg gratings. The proposed device consists of two sinusoidally modulated distributed Bragg reflectors (DSBRs) separated by a central $\pi/2$ phase-shifted cavity, forming a localized defect mode within the Bragg stopband and enabling narrowband resonant transmission. The spectral response is first investigated using three-dimensional finite-difference time-domain (3D FDTD) simulations to evaluate the effect of reflector length on the resonance characteristics. Based on the numerical analysis, devices with different Bragg reflector lengths were fabricated on the SOI platform using high-resolution electron-beam lithography (EBL) and plasma etching and subsequently characterized experimentally. Among the investigated configurations, the device with a DSBR length of $48\ \mu\text{m}$ per side demonstrated the most favorable filtering performance. The measured transmission spectrum exhibits a resonance near $1550\ \text{nm}$ with a linewidth of approximately $0.25\ \text{nm}$, corresponding to a quality factor of $Q \approx 6200$, an extinction ratio of approximately $22\ \text{dB}$, and a fiber-to-fiber insertion loss of $4\text{--}5\ \text{dB}$. The propagation loss of the Bragg resonator was measured to range from 2.45 to $4.6\ \text{dB/cm}$. The overall agreement between the simulated and measured spectra confirms that the fabricated devices reproduce the expected resonant behavior. This compact, experimentally validated architecture can be used for integrated wavelength-channel selection, wavelength-interrogated sensing, microwave-photonic filtering, and other narrowband photonic applications.

Index Terms—Optical filter, quality factor, silicon-on-insulator, sinusoidal Bragg gratings, phase-shifted cavity, finite-difference time-domain, electron-beam lithography.

I. INTRODUCTION

SILICON photonics has become a transformative platform that offers compact, scalable, and energy-efficient solutions for applications such as high-speed optical communication, signal processing, quantum information, optical sensing, lidar, and microwave photonics [1]–[4]. Photonic integrated circuits (PICs) are built from a set of universal components, including optical waveguides, crossings, mode converters, power splitters, interferometric devices, filters, resonant structures, and couplers. Among these building blocks, narrowband optical filters play a vital role in modern photonic systems. By transmitting a narrow range of wavelengths and effectively blocking adjacent spectra, they provide the spectral precision required for high-performance optical functionalities [5]–[7].

In optical communication systems, they enable per-channel add/drop operations and minimize inter-channel crosstalk in dense wavelength-division multiplexing (DWDM) networks. In laser systems, they stabilize emission characteristics by suppressing side modes and narrowing the linewidth to achieve high spectral purity. In spectroscopic and biochemical sensing, they isolate distinct absorption or emission lines, thereby enhancing detection accuracy and sensitivity. In microwave photonics, narrowband filters allow tunable optical-to-RF conversion and efficient interference suppression in integrated front-end modules [8]–[13].

Several filter technologies have been explored, including Fabry–Pérot etalons [14]–[19], fiber Bragg gratings [20]–[23], ring-assisted Mach–Zehnder interferometers [24]–[26], Brillouin-based active filters [18], [27]–[29], and microring and microdisk resonators [30]–[32]. However, each of these approaches exhibits inherent limitations when simultaneously targeting compact footprints, high extinction ratios, low insertion losses, and spectrally clean single-line operation on silicon-on-insulator (SOI) platforms. Conventional Fabry–Pérot cavities, whether implemented with cleaved facets, integrated distributed reflectors, or partially reflecting interfaces, often lack sufficiently sharp, rectangular passbands and exhibit pronounced sidelobes unless multiple stages are cascaded or apodized structures are employed. Fiber Bragg gratings naturally offer strong reflection and flexible spectral engineering but are typically realized in optical fiber, leading to packaging complexity and limited monolithic integration with planar photonic circuits. Ring-assisted Mach–Zehnder interferometers combine interferometric and resonant effects to improve filter selectivity and passband shaping. Nonetheless, these architectures introduce additional design complexity and sensitivity to path-length imbalance, and often demand careful thermal control to maintain the desired interference condition. Brillouin-based active filters can provide ultra-narrow linewidths and high rejection, but they rely on stimulated Brillouin scattering in specialized waveguides or fibers, require high optical power and precise pump–probe alignment, and generally involve bulky or complex setups that are less attractive for dense, low-power integrated PICs.

Microring and microdisk resonators fabricated on SOI platforms have been widely employed for narrowband optical filtering due to their compact size and high theoretical quality factors. However, despite their popularity, these resonant structures suffer from several fundamental practical limitations. Their operation relies critically on evanescent coupling

between a straight bus waveguide and a curved resonator, and often between the resonator and a dedicated drop waveguide. Achieving the desired coupling coefficients and critical-coupling condition typically requires bus–ring and ring–drop gaps on the order of, or below, 100 nm. Maintaining such sub-100-nm gaps with tight tolerances across an entire wafer is highly challenging in practice due to lithographic proximity effects, etch bias, and line-edge roughness. Consequently, the coupling strength and extinction ratio exhibit significant device-to-device variability, and small fabrication deviations can shift the device away from its intended operating point.

In addition, microring resonators inherently support a periodic comb of resonances separated by the free spectral range (FSR). At the drop port, this results in multiple transmission peaks, although typically only one resonance is functionally useful. The remaining resonances are parasitic and often require additional filtering stages or cascaded architectures for suppression, thereby increasing circuit complexity. Although numerical simulations frequently report quality factors exceeding 10^4 , such ultra-high- Q performance is rarely reproduced experimentally. In practice, bend-induced radiation loss, sidewall roughness, dimensional fluctuations, and wafer-scale nonuniformities broaden the resonance linewidth and limit achievable Q , especially for compact radii. Furthermore, the resonance wavelength is highly sensitive to small variations in ring radius and waveguide dimensions, rendering the spectral response vulnerable to fabrication tolerances, thermal drift, and packaging conditions. Mitigating bending loss in high- Q designs often necessitates ring radii of several to tens of micrometers, leading to increased footprint and imposing constraints on routing density in large-scale photonic integrated circuits.

Waveguide Bragg gratings (WBGs) have emerged as an attractive solution for wavelength-selective filtering in integrated photonic circuits. WBGs are typically implemented on SOI platforms through periodic sidewall corrugations or waveguide-width modulation, which introduce periodic perturbations in the effective refractive index and generate Bragg reflection at the designed wavelength. Conventional implementations predominantly employed rectangular grating profiles, which produced broad stopbands suitable for reflective filtering. However, the abrupt refractive-index discontinuities associated with rectangular corrugations generally increase scattering loss, enhance sidelobe formation, and increase sensitivity to sidewall roughness and fabrication imperfections [9]. To improve spectral performance, subsequent studies introduced apodized and smoothly modulated grating profiles to suppress sidelobes, reduce insertion loss, and enhance fabrication tolerance. More recent developments have focused on spectral shaping, bandwidth control, reflectivity engineering, and optimization-driven grating design while preserving compact device footprints [33]. Nevertheless, achieving a balanced combination of ultra-narrow bandwidth, high extinction ratio, low propagation loss, and fabrication robustness remains a significant challenge in WBG-based optical filters. Motivated by these challenges, this work proposes a new integrated narrowband filter architecture monolithically implemented on SOI platform. Unlike previous studies, the novelty of the

proposed work does not lie in introducing another Bragg grating profile or a new grating mechanism. Instead, it resides in the development of a compact resonant transmission filter architecture in which two distributed sinusoidal Bragg reflectors (DSBRs) are combined with a compact $\pi/2$ phase-shifted cavity. In conventional WBGs, the periodic refractive-index modulation primarily produces a broad reflective stopband, rejecting a finite wavelength band through distributed Bragg reflection. In contrast, the proposed architecture fundamentally changes the operating principle by introducing a compact $\pi/2$ phase-shifted cavity between the two DSBRs, thereby creating a strongly localized defect mode within the Bragg stopband. Consequently, rather than functioning as a conventional reflective Bragg filter, the proposed device operates as a compact in-line narrowband resonant transmission filter, supporting a single isolated transmission resonance while maintaining strong rejection of adjacent wavelengths. This transformation from a distributed reflective stopband filter into a localized high- Q resonant transmission filter constitutes the principal architectural innovation of the proposed work. A distinguishing feature of the proposed architecture is the use of sinusoidally modulated sidewall gratings, which reduce scattering loss, suppress sidelobes, and enhance mirror reflectivity, thereby improving spectral purity and transmission efficiency. Equally important, the one-period $\pi/2$ phase-shifted cavity generates a ripple-free isolated resonance without increasing the device footprint, enabling compact integration while maintaining excellent spectral selectivity. The proposed architecture is further supported by a comprehensive design framework that combines coupled-mode/Fabry–Perot analytical modeling, particle swarm optimization (PSO), and full-wave three-dimensional finite-difference time-domain (3D FDTD) simulations to optimize the grating period, modulation amplitude, cavity length, and number of Bragg periods for simultaneous linewidth minimization and transmission maximization. The optimized device is fabricated using CMOS-compatible SOI technology and experimentally characterized, demonstrating a resonance centered at 1550 nm with a linewidth of approximately 0.25 nm, corresponding to a measured quality factor of $Q \approx 6200$, in excellent agreement with the analytical and numerical predictions. Compared with conventional filter architectures—including Fabry–Pérot etalons (limited spectral rectangularity), rectangular-grating reflectors (higher scattering loss and sidelobes), Brillouin-based active filters (complexity and high cost), microring resonators (tight gap tolerances, multiple parasitic resonances, and large footprint), and conventional WBGs (broad stopband filtering response)—the proposed DSBR-based phase-shifted cavity offers a compact, in-line, and fabrication-friendly solution that delivers a single narrow transmission peak with high extinction ratio and low intrinsic loss. Its combination of narrow linewidth, strong out-of-band rejection, extinction ratio, and low intrinsic loss. Its combination of narrow linewidth, strong out-of-band rejection, and SOI compatibility makes the device particularly attractive for dense wavelength-division multiplexing, precision optical sensing, microwave photonics, and quantum photonic signal routing.

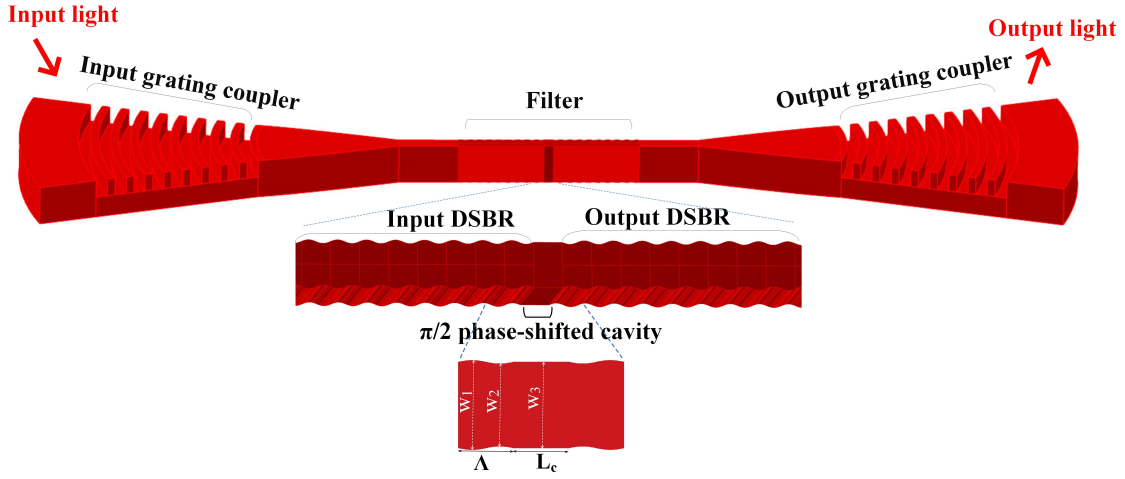


Fig. 1. Schematic of the proposed silicon photonic narrowband filter consisting of an input grating coupler, input DSBR, $\pi/2$ phase-shifted cavity, output DSBR, and output grating coupler. Each DSBR is implemented as a sinusoidally corrugated Bragg waveguide with period $\Lambda = 320$ nm and $N = 150$ periods (total length $48 \mu\text{m}$ per reflector), where the waveguide width is smoothly modulated between $w_1 = 520$ nm and $w_2 = 480$ nm. The cavity and access waveguides have a uniform width of $w_3 = 500$ nm, and the $\pi/2$ phase-shifted cavity length is $L_c = 320$ nm.

II. PROPOSED FILTER

Figure 1 illustrates the perspective view of the proposed narrowband optical filter, implemented on a monolithic silicon photonic platform to achieve high spectral selectivity and efficient fiber interfacing. The device is fabricated on a standard SOI substrate consisting of a 220 nm thick top silicon layer for waveguide definition, a buried silicon dioxide (SiO_2) layer serving as the lower cladding, and a silica overcladding as the upper cladding. This material stack provides strong vertical optical confinement, structural robustness, and environmental protection, while the overcladding layer enables fine control of the modal effective index.

The filter architecture comprises five cascaded functional sections that collectively form a compact on-chip Fabry–Perot resonator. Monolithically integrated grating couplers are positioned at the input and output ports to enable efficient vertical coupling between standard single-mode fibers and the planar silicon waveguide circuit. This configuration minimizes coupling loss and ensures compatibility with practical fiber-based photonic systems. The core filtering function is realized using two identical DSBRs acting as high-reflectivity mirrors that enclose a centrally positioned $\pi/2$ phase-shifted cavity. Each DSBR is implemented using the geometrical parameters obtained from the PSO algorithm described in the following section. The optimized grating period is $\Lambda = 320$ nm, and each reflector comprises 150 periods, corresponding to a total length of $48 \mu\text{m}$. The Bragg sections feature sinusoidally modulated sidewalls with waveguide widths smoothly varying between $w_1 = 520$ nm and $w_2 = 480$ nm. In contrast, the cavity and access waveguides maintain a uniform optimized width of $w_3 = 500$ nm to ensure modal stability and reduce propagation loss. The cavity length is set to the optimized value of $L_c = 320$ nm, introducing an exact $\pi/2$ phase discontinuity within the periodic structure.

The DSBRs establish a pronounced photonic stopband characterized by strong reflection. The inserted $\pi/2$ phase shift

creates a localized defect mode near the center of this stopband, enabling the formation of a narrow transmission peak with high spectral purity. Physically, the structure operates as a high-finesse Fabry–Perot resonator: wavelengths within the stopband are strongly reflected, whereas the resonant wavelength satisfying the cavity condition undergoes constructive interference, resulting in enhanced field confinement within the phase-shift region and efficient transmission through the output reflector.

A key design advancement is the adoption of sinusoidal sidewall modulation instead of conventional rectangular corrugations. The smooth geometric transition reduces abrupt discontinuities along the propagation direction, thereby mitigating scattering losses and suppressing radiation leakage. This approach enhances the resonance quality factor, improves out-of-band rejection, and yields a cleaner spectral response. The combined use of sinusoidal Bragg reflectors and a precisely engineered $\pi/2$ phase-shifted cavity enables superior wavelength selectivity, high transmission efficiency, and a compact device footprint compared to conventional distributed Bragg reflector-based filters.

III. MATHEMATICAL BACKGROUND

In this section, we present an analytical framework for the transmission of the proposed filter—comprising an input DSBR, a $\pi/2$ phase-shifted cavity, and an output DSBR. Our approach integrates coupled-mode theory (CMT) [34], [35] to model Bragg gratings with a Fabry–Perot description of the cavity–mirror interaction. The resulting expressions offer clear physical insight into device operation and enable direct comparison with measurements, including the stopband width and the resonance linewidth.

A. Bragg Reflector Model

A distributed Bragg reflector acts as a wavelength-selective mirror due to the periodic modulation of the effective index.

For a sinusoidally modulated Bragg grating of length L , the forward- and backward-propagating wave envelopes, $A(z)$ and $B(z)$, satisfy the coupled-mode equations:

$$\frac{dA(z)}{dz} = j\delta A(z) + j\kappa B(z), \quad (1)$$

$$\frac{dB(z)}{dz} = -j\delta B(z) + j\kappa A(z), \quad (2)$$

where κ is the (real) coupling coefficient proportional to the index modulation depth, and the detuning, $\delta(\lambda)$, is defined as

$$\delta(\lambda) = \beta(\lambda) - \pi/\Lambda, \quad (3)$$

where Λ is the grating period, and $\beta(\lambda)$ is the propagation constant of the guided mode, defined as

$$\beta(\lambda) = \frac{2\pi}{\lambda} n_{\text{eff}}(\lambda), \quad (4)$$

with $n_{\text{eff}}(\lambda)$ denoting the effective index of the guided mode. The parameter δ measures how far the operating wavelength is from the Bragg condition. When $\delta = 0$, the wavelength satisfies the Bragg condition and reflection is strongest. As $|\delta|$ increases, the wave becomes off-resonance and transmission increases. The coupling coefficient κ quantifies the strength of the Bragg interaction. For index-modulated gratings, it can be expressed as

$$\kappa(\lambda) = \frac{\pi}{\lambda} \eta \Delta n_{\text{eff}}, \quad (5)$$

where Δn_{eff} is the effective index modulation (first Fourier component of the periodic perturbation) and $\eta \in (0, 1]$ is the mode-grating overlap factor. For a purely sinusoidal index profile, $n(z) = n_0 + \Delta n \cos(2\pi z/\Lambda)$, this reduces to

$$\kappa(\lambda) \approx \frac{\pi}{\lambda} \Delta n_{\text{eff}}. \quad (6)$$

A larger modulation or stronger overlap yields a stronger reflection band. For a width-modulated sinusoidal waveguide (DSBR),

$$\kappa(\lambda) \approx \frac{\pi}{\lambda} \left(\frac{\partial n_{\text{eff}}}{\partial w} \right) \frac{\Delta w}{2}. \quad (7)$$

where $\partial n_{\text{eff}}/\partial w$ is the sensitivity of the guided-mode effective index to waveguide width and Δw is the modulation depth of the sidewall. Solving (1)–(2) yields the closed-form complex transmission and reflection amplitudes of a uniform Bragg grating of length L :

$$t(\lambda) = \frac{1}{\cosh(\sigma L) - j \frac{\delta}{\sigma} \sinh(\sigma L)}, \quad (8)$$

$$r(\lambda) = \frac{j \frac{\kappa}{\sigma} \sinh(\sigma L)}{\cosh(\sigma L) - j \frac{\delta}{\sigma} \sinh(\sigma L)}, \quad (9)$$

where σ is the effective coupling factor, defined as

$$\sigma \equiv \sqrt{\kappa^2 - \delta^2} \quad (10)$$

At exact Bragg resonance ($\delta = 0$), a sufficiently long grating yields near-unity reflection and suppressed transmission. Losses due to scattering or absorption can be included by modifying $\delta \rightarrow \delta + j\alpha/2$, where α is the power attenuation constant.

B. $\pi/2$ phase-shifted cavity

To carve a single, narrow resonance within the Bragg stopband, we introduce a controlled phase discontinuity between the two Bragg mirrors. In this work, the defect is a quarter-wave ($\pi/2$) phase shift, which places a localized defect mode exactly at the stopband center, maximizing symmetry and field build-up. This choice yields a high- Q , high-contrast transmission peak with low sidelobes and minimal group-delay ripple, while preserving the grating period and the overall compactness of the filter. The single-pass phase accumulated by the cavity is

$$\phi(\lambda) = \beta(\lambda) L_c + \phi_q, \quad \phi_q = \frac{\pi}{2}, \quad (11)$$

where L_c is the physical cavity length (here one grating period). The $\pi/2$ defect places a localized resonance at the center of the Bragg stopband so that only one wavelength satisfies the constructive-interference condition, yielding narrowband transmission. Intuitively, the phase defect acts as a selective “resonant gate” within the reflective Bragg mirrors, allowing light at the defect wavelength to tunnel through while other wavelengths remain strongly suppressed.

C. Fabry–Pérot Formulation of the Bragg–Cavity–Bragg System

The two DSBRs separated by the defect section form a Fabry–Pérot (FP) resonator. Let (t_1, r_1) and (t_2, r_2) denote the complex amplitude transmission and reflection coefficients of the input and output DSBRs, respectively, and let $\phi(\lambda)$ be the single-pass phase of the defect section (including any discrete phase shift). The FP transmission amplitude is

$$t_{\text{FP}}(\lambda) = \frac{t_1(\lambda) t_2(\lambda) e^{j\phi(\lambda)}}{1 - r_1(\lambda) r_2(\lambda) e^{j2\phi(\lambda)}}, \quad (12)$$

so that the power transmission is $T(\lambda) = |t_{\text{FP}}(\lambda)|^2$. Resonances arise when the total round-trip phase satisfies

$$2\phi(\lambda) + \theta_{r_1}(\lambda) + \theta_{r_2}(\lambda) = 2m\pi, \quad m \in \mathbb{Z}, \quad (13)$$

where $\theta_{r_i}(\lambda)$ ($i = 1, 2$) are the reflection phases of the Bragg mirrors. This condition enforces constructive interference of successive cavity round trips, producing a sharp transmission peak within the DSBR stopband.

D. Stopband Width

The Bragg stopband width can be related to the coupling strength and the group index. Linearizing the propagation constant near the Bragg wavelength as $\beta(\lambda) \approx \beta_B + (\omega - \omega_B)/v_g$, the stopband (in wavelength) is approximated by

$$\Delta\lambda_{\text{SB}} \approx \frac{2\kappa\lambda_B^2}{\pi n_g}, \quad (14)$$

where $n_g \equiv c/v_g$ is the group index. This expression shows that the stopband broadens with increasing grating coupling κ .

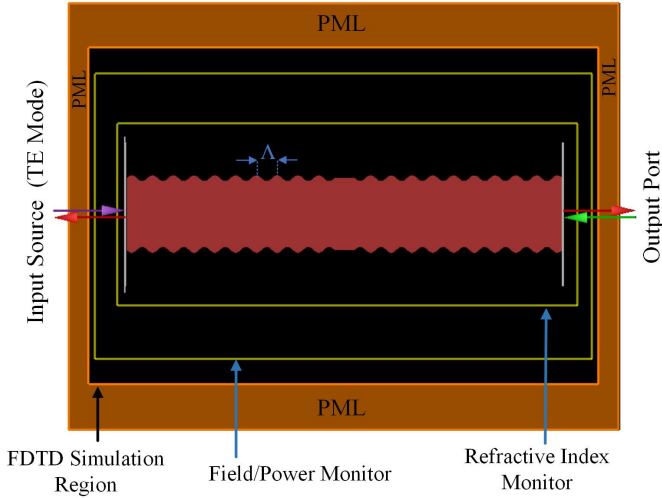


Fig. 2. Top view of the simulated DSBR-based Bragg filter for $N = 10$, showing the input DSBR, the central $\pi/2$ phase-shifted cavity, and the output DSBR. The simulation domain includes the TE fundamental-mode excitation source, power and field monitors, effective refractive-index monitor, and PML boundary conditions.

E. Resonance Linewidth and Quality Factor

Inside the stopband, the $\pi/2$ phase defect supports a single, narrow transmission resonance. For high-reflectivity DSBR mirrors, the full-width at half-maximum (FWHM) can be approximated by

$$\Delta\lambda_{\text{FWHM}} \approx \frac{1 - |r_1 r_2|}{\pi \sqrt{|r_1 r_2|}} \frac{\lambda_0^2}{n_g (2L_c)}, \quad (15)$$

where λ_0 is the resonance wavelength, n_g is the group index, and L_c is the physical cavity length. The associated quality factor is

$$Q = \frac{\lambda_0}{\Delta\lambda_{\text{FWHM}}}. \quad (16)$$

For a uniform sinusoidal Bragg reflector of period Λ and length $L = N\Lambda$, the on-Bragg ($\delta = 0$) transmission and reflection amplitudes obtained from (8)–(9) reduce to

$$t(N) = \text{sech}(\kappa N\Lambda), \quad r(N) = j \tanh(\kappa N\Lambda), \quad (17)$$

so that the power reflectivity is

$$R(N) = |r(N)|^2 = \tanh^2(\kappa N\Lambda). \quad (18)$$

Thus, increasing the number of periods N exponentially increases the DSBR reflectivity, deepens the stopband, and, through (15)–(16), narrows the linewidth of the defect-mode and increases the cavity quality factor. In practice, intrinsic loss and phase distortion limit the useful range of N , leading to an optimal mirror length, consistent with the trends observed in the simulated spectra of Section IV-B.

IV. SIMULATION STUDY AND RESULTS

A. Numerical Modeling and Optimization Framework

Figure 2 illustrates the top-view layout of the simulated DSBR-based resonant filter, comprising the input DSBR, the central $\pi/2$ phase-shifted cavity, and the output DSBR. For

clarity of visualization, the structure is depicted with grating periods $N = 10$; in practice, larger values of N correspond solely to an increased number of periodic corrugations, while all other geometric parameters remain unchanged.

To accurately capture intrinsic filtering behavior while maintaining computational tractability, the numerical domain is restricted to the resonant core consisting of the two DSBRs and the defect cavity. The input and output grating couplers are excluded from the simulation in order to isolate the fundamental cavity–Bragg interaction and eliminate extraneous coupling effects. Since the performance of silicon photonic grating couplers has been thoroughly validated in prior experimental and numerical studies [36]–[38], their omission allows the spectral characteristics reported here to directly reflect the intrinsic resonant dynamics of the filter itself.

The device is modeled on a silicon-on-insulator platform, where the silicon (Si) device layer is patterned atop a SiO_2 substrate. Both materials are treated as wavelength-dispersive within the 1490–1610 nm spectral range using experimentally validated complex refractive indices, $\tilde{n}(\lambda) = n(\lambda) + i k(\lambda)$, imported as spectral material data. Although silicon exhibits minimal absorption in this band, a finite extinction coefficient $k(\lambda)$ is retained to accurately account for intrinsic propagation losses and their influence on resonance linewidth and quality factor. The silica substrate is modeled as nearly lossless. This dispersive treatment ensures physically realistic prediction of spectral response and insertion loss.

A continuous-wave TE fundamental mode is launched into the input waveguide and spectrally swept across the wavelength range of interest. All simulation boundaries are terminated using perfectly matched layers (PMLs) in (x, y, z) to suppress spurious reflections. An adaptive non-uniform meshing strategy is adopted to balance numerical precision and computational efficiency. In regions of strong field localization—particularly within the DSBR and cavity sections—the mesh resolution is refined to approximately 5 nm to accurately resolve rapid spatial field variations. In contrast, regions with weaker field gradients employ a coarser mesh of approximately 25 nm to reduce memory consumption and computational time. Power monitors are used to extract transmission spectra and insertion loss, electromagnetic field monitors capture resonant mode distributions, and effective refractive-index monitors evaluate modal confinement. All simulations are performed using the FDTD method, which is especially well suited for broadband analysis of high-index contrast, dispersive, and strongly resonant photonic structures.

Building upon this robust numerical foundation, the geometrical parameters of the DSBR-based cavity are systematically optimized using a PSO algorithm. PSO is a population-based stochastic optimization method inspired by collective social behavior, wherein a swarm of candidate solutions explores the multidimensional parameter space. Each particle represents a potential set of geometric variables and iteratively updates its position according to both its individual best-known solution and the globally best solution identified by the swarm. This cooperative exploration strategy enables efficient convergence toward global optima while mitigating entrapment in local minima—an important consideration for nonlinear resonant

photonic systems characterized by complex parameter interdependencies.

The optimization objective is to achieve a narrow transmission peak centered at 1550 nm with a high quality factor while simultaneously maximizing the transmission amplitude at the filter output. The design variables include sinusoidal modulation widths w_1 and w_2 , uniform waveguide width w_3 , grating period Λ , cavity length L_c , and number of Bragg periods N . To directly enhance spectral selectivity, the fitness function is defined as $F = T_{\text{peak}}/\text{FWHM}$, thereby promoting high transmission efficiency together with minimal resonance linewidth. An additional constraint enforces precise alignment of the resonant wavelength at 1550 nm. Through iterative swarm-based exploration of the design space, the PSO algorithm converges to a globally optimized configuration. The resulting optimized structure exhibits a grating period of $\Lambda = 320$ nm with $N = 150$ periods per reflector, corresponding to a total reflector length of $48 \mu\text{m}$. The DSBR sections employ sinusoidally modulated sidewalls with the waveguide width smoothly varying between $w_1 = 520$ nm and $w_2 = 480$ nm, while the cavity and access waveguides maintain a uniform width of $w_3 = 500$ nm to preserve modal stability and minimize propagation loss. The cavity length is defined as $L_c = 320$ nm, introducing an exact $\pi/2$ phase discontinuity within the periodic structure and enabling the formation of a high-finesse defect resonance precisely at the desired operating wavelength. The design parameters were determined by jointly considering spectral performance, device compactness, and fabrication feasibility. The Bragg period was selected to position the resonance wavelength at approximately 1550 nm. Sinusoidal sidewall modulation was adopted to suppress sidelobes, reduce scattering losses, and improve fabrication tolerance compared with conventional rectangular gratings. A compact $\pi/2$ phase-shifted cavity was incorporated between the distributed sinusoidal Bragg reflectors to generate a single strongly localized defect mode within the Bragg stopband, thereby enabling a narrow resonant transmission peak without increasing the device footprint. Finally, the number of Bragg periods was optimized to provide an appropriate balance among reflector reflectivity, resonance linewidth, insertion loss, and overall device length.

B. Spectral Response

Figure 3 illustrates the transmission spectra of the proposed DSBR-based resonant filter for different numbers of Bragg periods (N) in each reflector. In every panel, two curves are presented: the dashed blue curve corresponds to the analytical model derived from the theoretical framework detailed in Section III, while the solid red curve represents the full-wave numerical results obtained using the FDTD method. The close agreement between the two curves throughout the wavelength range and for all values of N confirms that the analytical formulation accurately captures the essential physics governing the phase-shifted Bragg cavity, including stopband formation, defect-mode resonance, and linewidth evolution.

The progression from panels (a) to (i) reveals how the spectral response is fundamentally governed by the reflectivity

of the DSBRs. For very small values of N , such as $N = 1$ [Fig. 3(a)], the reflectivity of the Bragg sections is extremely weak. Under these conditions, the structure does not form a photonic stopband and no effective cavity resonance is established. Both analytical and FDTD results show an almost flat transmission profile, indicating that the phase-shift region alone is insufficient to produce spectral selectivity without adequate mirror feedback. As N increases to 10 and 30 [Fig. 3(b) and (c)], the periodic modulation begins to generate a shallow stopband around 1550 nm. A weak defect-induced resonance appears at the center of this emerging stopband. However, because the mirror reflectivity remains moderate, the cavity finesse is limited, resulting in a broad transmission peak with relatively low contrast. The analytical and numerical curves continue to overlap closely, demonstrating that the theoretical model reliably predicts the onset of cavity formation.

Further increasing N to 50 and 100 [Fig. 3(d) and (e)] significantly strengthens the mirror reflectivity, thereby enhancing optical confinement within the $\pi/2$ phase-shifted cavity. The increased reflectivity improves the effective cavity finesse, leading to sharper resonance features and deeper stopband minima. The narrowing of the transmission peak is clearly observed in both models, reflecting the increased photon lifetime inside the cavity. The optimal spectral performance is achieved at $N = 150$ [Fig. 3(f)], where a well-defined, narrow transmission peak is observed with a full width at half maximum (FWHM) of approximately 0.25 nm, corresponding to a quality factor of $Q \approx 6200$. At this operating point, the system achieves an optimal balance between mirror reflectivity and coupling efficiency. The reflectors are sufficiently strong to provide high confinement and field enhancement within the cavity, yet not so strong as to severely limit energy coupling into the defect region. This balance results in maximum resonance visibility and spectral selectivity. When N is increased beyond this optimal value, as shown in panels (g) and (h) for $N = 200$ and $N = 250$, the reflectors approach near-unity reflectivity. Although the stopband depth continues to increase, the structure gradually transitions toward an undercoupled regime. In this regime, the coupling of optical power into the cavity becomes increasingly limited, reducing intracavity field buildup despite the high mirror strength. Consequently, the transmission peak amplitude decreases, and the spectral ripple becomes more pronounced. At $N = 300$ [Fig. 3(i)], the structure behaves predominantly as a conventional Bragg band-stop filter. The stopband extends over approximately 13 nm (1543.5–1556.5 nm), and the defect-induced transmission peak becomes strongly suppressed. Both analytical and FDTD results consistently predict this transition, confirming that excessive mirror reflectivity effectively inhibits resonant transmission.

Overall, the spectral evolution observed across panels (a)–(i) demonstrates that the filter response is fundamentally governed by the reflectivity-dependent dynamics of the DSBR-based Fabry–Pérot cavity. The evolution of the transmission peak with increasing number of grating periods N can be physically understood from the behavior of the distributed Bragg mirrors forming the cavity. For small N , the mirror reflectivity is weak and no pronounced photonic stopband is established. As a

result, the cavity lacks sufficient feedback to support strong field localization, and the resonance either remains broad or does not form.

As N increases, the mirror reflectivity grows approximately as $R \approx \tanh^2(\kappa N \Lambda)$, leading to stronger optical confinement and an increased photon lifetime inside the cavity. This enhancement in confinement improves the cavity finesse, resulting in progressive linewidth narrowing and higher spectral selectivity. In this regime, the resonance becomes sharper and more pronounced due to efficient constructive interference and sustained intracavity field buildup. However, when N becomes excessively large, the mirrors approach near-unity reflectivity and the system transitions toward an undercoupled regime. Under these conditions, coupling of external optical power into the cavity becomes inefficient, limiting intracavity energy accumulation despite the strong reflectors. Consequently, the transmission peak amplitude decreases and may eventually become strongly suppressed. For sufficiently large N , the structure behaves predominantly as a high-reflectivity Bragg mirror rather than an efficiently coupled resonant cavity, and the defect-mode transmission is significantly reduced. Therefore, increasing N initially enhances resonance sharpness by improving optical confinement and cavity finesse, but excessively large values degrade coupling efficiency and transmission. These results clearly establish the existence of an optimal number of grating periods that maximizes spectral selectivity while maintaining efficient resonant transmission.

While the analytical model provides clear physical insight into the resonance formation and its dependence on mirror strength, the FDTD simulations play a crucial role in accurately capturing dispersive material effects, finite-structure behavior, and realistic waveguide confinement. More importantly, the numerical framework is employed to determine the optimal geometrical parameters required to achieve the narrowest transmission peak centered at 1550 nm. In the present design, $N = 150$ provides the best compromise between linewidth minimization, transmission efficiency, and device compactness.

Figure 4 shows the simulated transmission (blue dashed line) and reflection (red solid line) spectra of the DSBRR-based filter for $N = 150$. A well-defined stopband is formed around 1550 nm, where the transmission drops sharply while the reflection approaches its maximum value, confirming strong distributed Bragg reflection. At the center of the stopband, a narrow resonance peak is observed in transmission, accompanied by a corresponding dip in reflection, indicating the $\pi/2$ phase-shifted cavity mode. The inset provides a magnified view of the resonance region, highlighting the symmetric spectral response and the complementary behavior between transmission and reflection.

V. FABRICATION AND MEASUREMENT

A. Fabrication Process

The achievement of high Q in grating-based resonators is challenging because of limited mirror reflectivity and short cavity lengths. However, advances in CMOS-compatible nanofabrication mitigate these challenges. Electron-beam

lithography (EBL) combined with optimized etching enables smooth sub-micrometer gratings [39], while sinusoidal modulation of the grating profile suppresses sidelobes and reduces scattering, thereby improving mirror reflectivity [14], [40]. We fabricated the proposed silicon photonic filter on SOI using high-resolution EBL and plasma etching. The fabrication process, detailed below, was designed to achieve the subwavelength precision required for high-performance PICs. The substrate consisted of a 220 nm-thick amorphous silicon device layer on a 2 μm buried oxide (SiO_2) layer, which was grown by plasma-enhanced chemical vapor deposition (PECVD) to ensure uniformity and minimize optical leakage. Prior to patterning, the wafer underwent a rigorous cleaning procedure with acetone and isopropanol rinses, followed by an oxygen-plasma treatment to remove organic contaminants and promote resist adhesion [41]. We then spin-coated a layer of positive-tone polymethyl methacrylate (PMMA) electron-beam resist, soft-baking it at 90–110 $^\circ\text{C}$ to remove residual solvent. The device layout, designed in KLayout and exported as a GDS-II file, was patterned using a Raith 152 EBL system. To define the intricate features of the DSBRRs, the phase-shifted cavity, and the grating couplers, we employed a fixed-beam moving-stage for writing strategy. This approach minimizes stitching errors across large areas by continuously translating the substrate under a stationary electron beam, thereby ensuring pattern fidelity and dimensional continuity in long-period gratings. Key lithographic parameters, including accelerating voltage, beam current, and area dose, were systematically optimized for nanoscale accuracy. Following exposure, the pattern was developed in a 1:3 methyl isobutyl ketone (MIBK): isopropanol (IPA) solution. The developed pattern was then transferred into the silicon layer via inductively coupled plasma reactive-ion etching (ICP-RIE). We used a mixed $\text{SF}_6/\text{C}_4\text{F}_8$ chemistry for general waveguide structures to achieve vertical sidewalls and a high etch rate. Etching parameters such as chamber pressure, RF power, and gas ratios were carefully controlled to reduce line-edge roughness and scattering losses. Any residual PMMA was subsequently removed with an oxygen-plasma ash. Finally, a silica cladding layer was deposited over the entire structure via PECVD. This top cladding enhances the device's mechanical stability, protects it from environmental perturbations such as moisture and particulate contamination, and improves optical performance by stabilizing the waveguide's effective refractive index.

Structural characterization by scanning electron microscopy (SEM) confirms the success of the fabrication methodology. Figure 5(a) shows a high-quality grating coupler, while Fig. 5(b) presents a micrograph highlighting a section of the input DSBRR, the central $\pi/2$ phase-shifted cavity, and part of the output DSBRR. The SEM images demonstrate excellent pattern transfer, dimensional fidelity, and smooth sidewalls. Collectively, these results validate the optimized process as a robust and precise pathway for realizing high- Q photonic devices.

From a process standpoint, the use of sinusoidal DSBRR mirrors does not fundamentally complicate the fabrication compared to standard rectangular gratings: the devices are

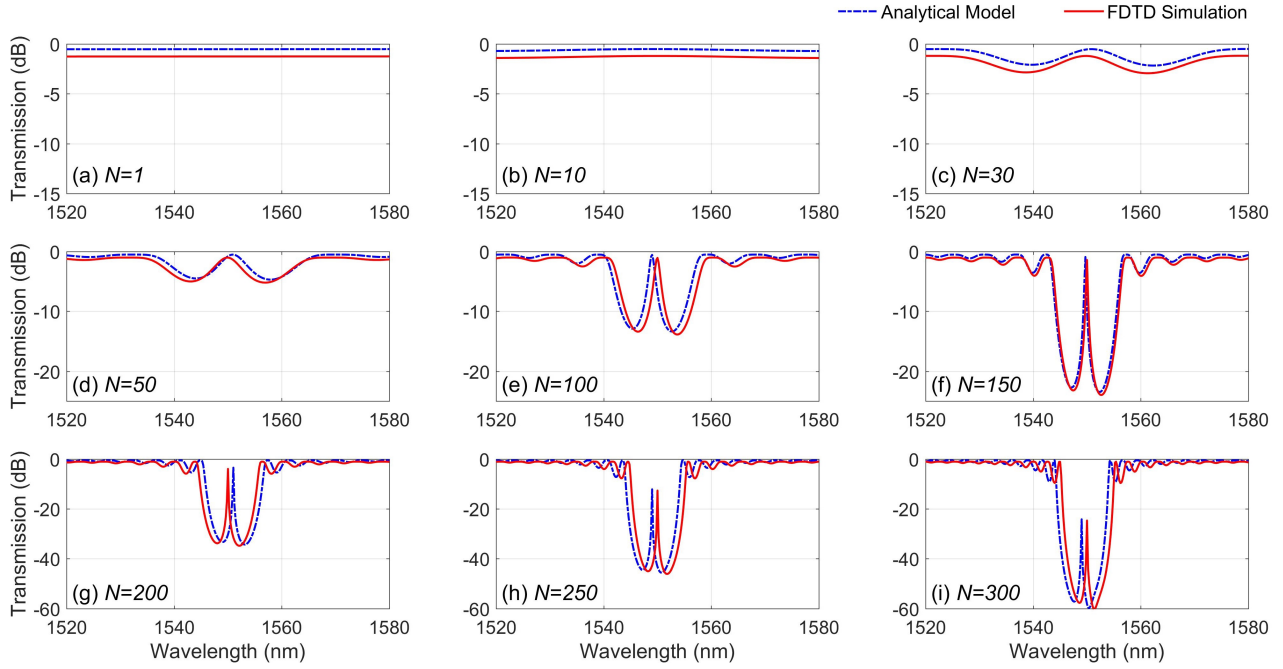


Fig. 3. Transmission spectra of the proposed DSBF-based $\pi/2$ phase-shifted filter over the wavelength range 1500–1600 nm for different numbers of Bragg periods N in each reflector. In each panel, the dashed blue curve represents the analytical model derived from the theoretical formulation in Section 3, while the solid red curve corresponds to full-wave FDTD simulation results. The spectra are shown for (a) $N = 1$, (b) $N = 10$, (c) $N = 30$, (d) $N = 50$, (e) $N = 100$, (f) $N = 150$, (g) $N = 200$, (h) $N = 250$, and (i) $N = 300$.

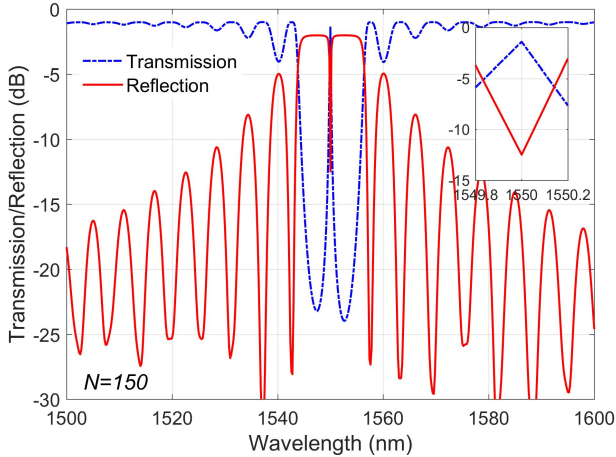


Fig. 4. Simulated transmission (blue dashed line) and reflection (red solid line) spectra of the DSBF-based filter for $N = 150$.

still realized with a single lithography step and a single ICP-RIE etch, and only the lateral sidewall contour is modified. EBL was employed here to accurately define the sinusoidal profile for this prototype, but the same pattern is compatible with stepper-based SOI foundry flows using appropriate mask design and optical proximity correction. It is worth noting that the slight contrast variation observed near the grating edges in Fig. 5(a) may, at first glance, suggest potential non-uniformity in the etching process. However, such contrast differences in SEM images are commonly associated with electron-beam charging effects, local surface topography vari-

ations, or imaging-angle artifacts, rather than actual structural or etch non-uniformity. Careful inspection of the grating coupler region confirms that the grating teeth exhibit uniform periodicity, consistent feature dimensions, and well-defined edges without evidence of structural collapse or irregular etch depth.

From a performance standpoint, significant etch non-uniformity would be expected to increase scattering loss and degrade coupling efficiency. However, the measured fiber-to-fiber insertion loss of approximately 4–5 dB is consistent with typical SOI grating couplers and is primarily attributed to intrinsic coupling efficiency rather than fabrication-induced scattering.

B. Experimental Characterization

The fabricated silicon-photonics filter was characterized using the setup of Figure 6(a), which comprises precision fiber holders, a vacuum device stage, and the device under test (DUT). A continuous-wave tunable laser source (CW-TLS; Keysight 81608A) provided a wavelength sweep from 1495 to 1640 nm with output power adjustable from 0 to +13 dBm (0.1 dB resolution). Light was injected through the input grating coupler using a single-mode fiber (SMF-28e⁺, Corning; core 8.2 μm , cladding 125 μm , attenuation < 0.18 dB/km at 1550 nm). A GRIN lens focused the beam onto the grating region, and the input fiber was set to an incidence angle of 12° relative to the chip normal to maximize coupling efficiency. The output from the on-chip grating coupler was collected by a second single-mode fiber and sent to a high-resolution optical spectrum analyzer (OSA), which enabled precise extraction of the resonance parameters.

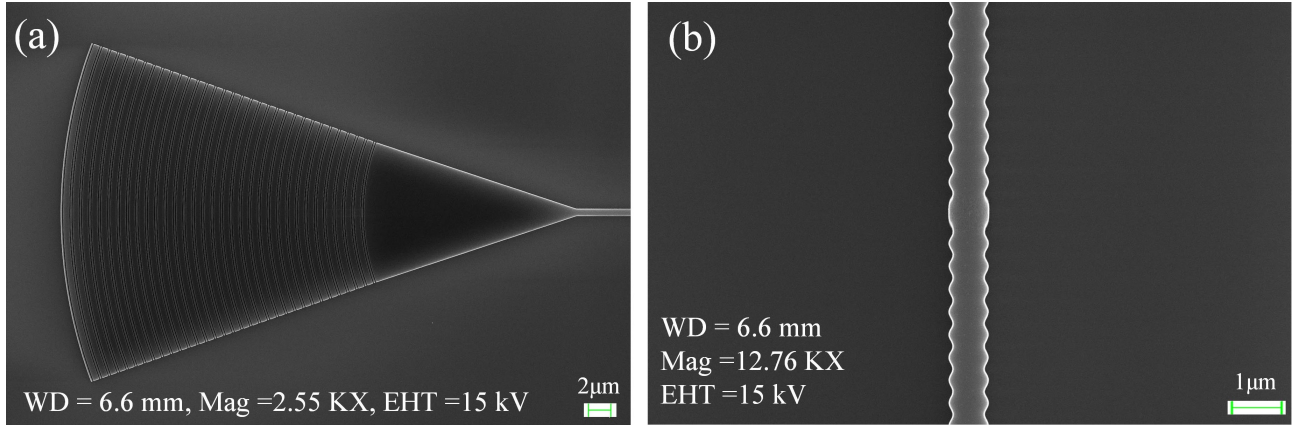


Fig. 5. (a) SEM image of the fabricated grating coupler, illustrating the coupling interface. (b) SEM micrograph highlighting a section of the input DSBR, the central $\pi/2$ phase-shifted cavity, and part of the output DSBR.

Figures 6(b)–(e) present the measured transmission spectra of the fabricated devices with $N = 1, 50, 150$, and 300 Bragg periods per DSBR, demonstrating the systematic evolution of the spectral response as the reflector strength increases. For $N = 1$ (Fig. 6(b)), the response closely matches that of two back-to-back grating couplers. The measured spectrum exhibits a smooth and broad envelope without any observable stopband or cavity resonance. This confirms that a single Bragg period is insufficient to establish distributed reflection or open a photonic bandgap, and the transmission is therefore dominated by the intrinsic spectral profile of the grating couplers. When the number of periods increases to $N = 50$ (Fig. 6(c)), distributed Bragg reflection begins to develop. Two shallow minima appear around the design wavelength, indicating the onset of stopband formation. A weak resonance feature emerges near 1550 nm, demonstrating partial cavity confinement; however, the reflectivity remains moderate and the spectral contrast is still limited. At $N = 150$ (Fig. 6(d)), the device reaches its optimal operating condition. A well-defined and symmetric stopband is clearly formed around 1550 nm, and a sharp resonance peak appears at the center of the bandgap. The inset provides a magnified view of the resonance, showing a peak transmission of -4.44 dB at 1550 nm with a 3 dB bandwidth of approximately 0.25 nm. This narrow linewidth indicates strong optical confinement and a high-quality resonant response. Compared to lower N values, both the stopband depth and the resonance sharpness improve significantly, yielding the best trade-off between reflectivity and insertion loss. For $N = 300$ (Fig. 6(e)), the mirrors become excessively strong. The stopband deepens dramatically (exceeding 60 dB suppression), but pronounced passband ripples appear due to increased multiple reflections and impedance mismatch. Moreover, the resonance contrast deteriorates, indicating a transition toward an increasingly undercoupled regime and performance degradation beyond the optimal reflector length.

The measured spectra in Fig. 6 exhibit slight asymmetry compared to the idealized simulation results shown in Fig. 3. In the numerical analysis, the input and output grating couplers were intentionally excluded to reduce computational

complexity, simulation time, and memory requirements, while isolating the intrinsic DSBR–cavity–DSBR resonant behavior. As a result, the simulated structure represents a perfectly symmetric Bragg–cavity–Bragg configuration, and the calculated spectra appear symmetric around the resonance wavelength. However, in the experimental measurements, the overall response inherently includes the spectral characteristics of the two grating couplers. Grating couplers exhibit wavelength-dependent coupling efficiency with a non-ideal and slightly asymmetric spectral envelope around 1550 nm. Consequently, the measured transmission becomes modulated by the coupler response, introducing observable asymmetry in the spectra. Additional practical factors may also contribute to this effect, including small fiber-alignment deviations, angular sensitivity of the couplers, polarization fluctuations, minor fabrication-induced phase imbalance between the two Bragg mirrors, and accumulated propagation loss. Despite these realistic experimental influences, the measured central resonance wavelength, linewidth (0.25 nm), and stopband evolution with increasing N remain in strong agreement with the simulation results, confirming that the intrinsic cavity dynamics are accurately captured by the theoretical and numerical models.

C. Loss and Extinction Metrics of the Proposed Filter

A complete evaluation of narrowband optical filters requires quantifying three key performance metrics: the extinction ratio, the insertion loss, and the intrinsic propagation loss. These parameters determine the spectral selectivity, power efficiency, and practical suitability of the on-chip device.

1) Extinction Ratio. The extinction ratio (ER) measures the contrast between the resonance transmission peak and the adjacent stopband, expressed in decibels (dB). It is defined as

$$ER = 10 \log_{10} \left(\frac{P_{\text{peak}}}{P_{\text{stop}}} \right), \quad (19)$$

where P_{peak} is the transmitted power at the resonance wavelength and P_{stop} is the transmitted power inside the stopband. For the optimized device with $N = 150$, the measured extinction ratio is approximately 22 dB, indicating strong

suppression of out-of-band wavelengths by the sinusoidal DSB mirrors and the phase-shifted cavity.

2) Insertion Loss. Insertion loss (IL) represents the total fiber-to-fiber loss through the system and is defined as

$$IL = -10 \log_{10} \left(\frac{P_{\text{out}}}{P_{\text{in}}} \right), \quad (20)$$

where P_{in} and P_{out} denote the optical powers at the input and output, respectively. In the fabricated device, the measured insertion loss is approximately 4–5 dB, dominated by the two grating couplers (each about 2–2.5 dB). The filter section itself contributes only a small additional loss, consistent with the low scattering behavior of sinusoidal Bragg gratings.

3) Intrinsic Propagation Loss. The intrinsic propagation loss quantifies the attenuation of guided light per unit length inside the DSB waveguide core and is expressed in dB/cm:

$$\alpha_{\text{int}} = -\frac{10}{L} \log_{10} \left(\frac{P(L)}{P(0)} \right), \quad (21)$$

where L is the waveguide length. In previous measurements on sinusoidal Bragg gratings fabricated on the same SOI platform [40], the intrinsic loss was found to be in the range of 2.45–4.6 dB/cm, close to that of straight reference waveguides. This confirms that the smooth sinusoidal modulation introduces only minimal scattering compared to rectangular corrugations.

The key benefit of the sinusoidal geometry is that it removes sharp corners and suppresses high-spatial-frequency components in the effective index modulation, thereby reducing coupling to radiation modes and mitigating sidewall-scattering losses [42]–[44]. In contrast, rectangular or square-tooth gratings introduce abrupt discontinuities and a richer Fourier spectrum, which are known to enhance scattering and excess loss in high-index-contrast platforms [45], [46]. Our simulation results, together with independent measurements on long sinusoidal Bragg sections fabricated on the same SOI platform [40], show that the propagation loss of sinusoidal DSBs remains comparable to that of straight reference waveguides and significantly lower than that of rectangular gratings with similar coupling strength. The extinction ratio of about 22 dB, insertion loss of 4–5 dB, and low intrinsic propagation loss together validate the high spectral selectivity and low-loss performance achieved by combining sinusoidal DSB mirrors with a $\pi/2$ phase-shifted cavity. These results align with the simulated spectra in Fig. 3 and confirm the practicality of the proposed filter for high-precision photonic applications.

D. Thermal Stability and Temperature-Sensing Potential

In the present implementation, the proposed filter operates as a fully passive device without any integrated tuning elements. The resonance wavelength is therefore determined solely by the geometrical parameters of the DSB mirrors and the $\pi/2$ phase-shifted cavity. Using the thermo-optic coefficient of silicon near 1550 nm ($dn/dT \approx 1.86 \times 10^{-4} \text{ K}^{-1}$ [47], [48]), the expected thermal drift of the resonance wavelength is approximately 70–80 pm/K, in line with typical values for SOI waveguides. Given the measured linewidth of ~ 0.25 nm, this

drift implies that temperature variations within about ± 2 K induce a resonance shift smaller than one full FWHM. In other words, for moderate temperature changes around the nominal operating point, the passband of the filter remains effectively aligned with the design wavelength and its transmission characteristics are only weakly perturbed. This level of stability is sufficient for normal laboratory conditions and many practical system environments where the chip temperature is controlled within a few kelvin. For larger temperature excursions, the thermo-optic effect causes the resonance wavelength to move by several linewidths across the spectrum. This behavior makes the proposed structure attractive as an integrated optical temperature sensor. For example, the filter could be placed near high-power electronic or photonic blocks (such as CPU cores, ASICs, or laser drivers) and used to monitor local temperature in real time by tracking the resonance wavelength. The resulting optical temperature signal could then be fed to a control unit to trigger or modulate cooling actions, providing a compact on-chip thermometer that leverages the intrinsic thermo-optic response of silicon.

Figure 7 provides a direct comparison between the FDTD simulation results and the recalculated measurement data for the proposed Bragg resonator, excluding the input and output grating couplers. In the measurement process, the structure with $N = 1$ was considered as a reference device. This structure consists of input/output grating couplers connected to a DSB- $\pi/2$ -phase-shifted cavity-DSB configuration with only one Bragg period on each side of the phase-shifted cavity. Due to the very limited number of Bragg periods, the reflector strength is negligible, and the structure behaves approximately as a conventional waveguide with minimal impact on optical propagation. Therefore, the measured transmission response of this reference device, shown in Fig. 6(b), primarily reflects the spectral contributions of the input/output grating couplers and the associated coupling path.

Using this reference response, the measured spectra of the devices with $N = 50, 150$, and 300 were de-embedded by removing the contributions of the grating couplers and the coupling path, thereby enabling extraction of the intrinsic response of the Bragg resonator. Figure 7 presents the resulting de-embedded experimental responses together with the corresponding FDTD simulations shown in Fig. 3.

For $N = 50$, the Bragg rejection band remains relatively weak because of the limited reflector strength, resulting in a shallower stopband response. For $N = 150$, the simulated and de-embedded measured spectra exhibit close agreement, including the position of the Bragg rejection band, the stopband minima, and the pronounced central defect-mode transmission window near 1550 nm. This result confirms the proper formation of the localized cavity mode and demonstrates a favorable balance between reflector strength and resonant transmission. For $N = 300$, the stronger Bragg reflection further suppresses the defect-mode transmission, indicating that the cavity moves toward an increasingly undercoupled regime as the reflector strength increases.

The remaining differences between the simulated and measured spectra, including variations in rejection depth, spectral ripple, and background transmission level, can be attributed to

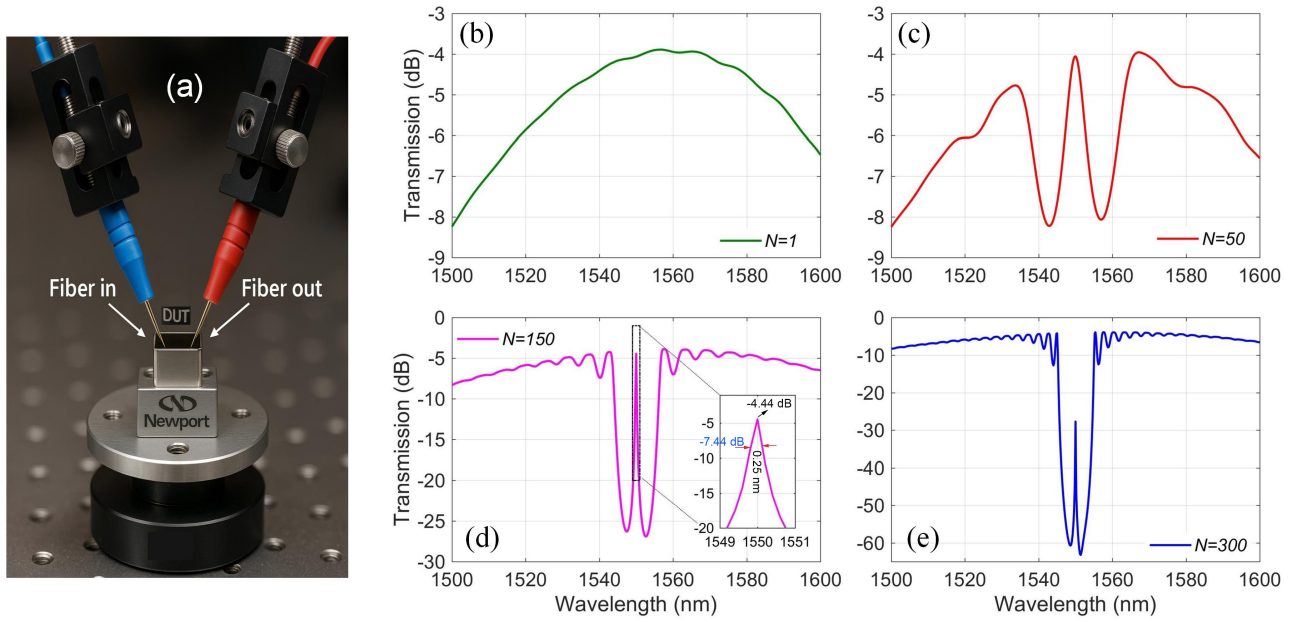


Fig. 6. (a) Experimental setup for optical characterization of the fabricated silicon-photonic filter, showing fiber-in/fiber-out coupling to the DUT via grating couplers. (b) Measured transmission for $N = 1$, where the filter behaves like two back-to-back grating couplers, capturing only the coupler spectral envelope without forming a stopband or a cavity resonance. (c) For $N = 50$, shallow reflection features emerge, indicating the onset of distributed Bragg reflection. (d) At $N = 150$, a well-defined stopband with a sharp resonance near 1550 nm is formed (inset: zoomed view). (e) For $N = 300$, the stopband becomes much deeper with increased ripples, indicating overly strong mirrors.

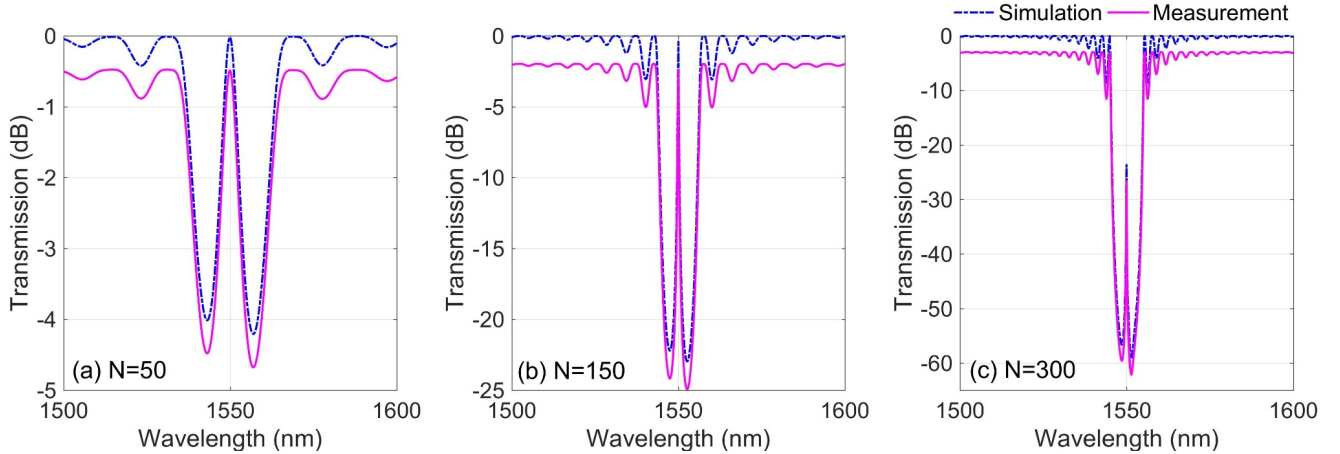


Fig. 7. Direct comparison of the FDTD simulation results and the recalculated, de-embedded measurement data for (a) $N = 50$, (b) $N = 150$, and (c) $N = 300$. The blue dash-dotted curves represent the FDTD simulations and the magenta solid curves represent the recalculated measurement responses after removal of the reference coupling response.

fabrication tolerances, phase deviations, polarization fluctuations, and other practical imperfections that are not included in the ideal FDTD model. Overall, the direct comparison confirms the same N -dependent spectral evolution in both simulation and experiment and validates the proposed DSBR- $\pi/2$ -phase-shifted cavity-DSBR resonator design.

E. Comparison with State-of-the-Art SOI Narrowband Filters

Table I benchmarks the proposed DSBR-based filter against a range of representative SOI narrowband filters, including microring and microdisk resonators, ring-assisted MZIs, rectangular and apodized Bragg gratings, contra-directional couplers, photonic crystal cavities, Brillouin-based active filters,

and hybrid/plasmonic architectures. As summarized in the table, many of these solutions can achieve either very narrow linewidths (e.g., high- Q microrings, photonic crystal nanocavities, Brillouin-based filters) or high extinction ratios, but typically at the cost of increased footprint, strong sensitivity to fabrication tolerances, complex layouts, or substantial thermal and system-level overhead. For instance, microring and Ring-assisted MZI filters require sub-100-nm coupling gaps and careful thermal stabilization and inherently produce a comb of resonances rather than a single isolated line; photonic crystal devices demand nanometer-scale control of lattice parameters and are highly sensitive to disorder; and Brillouin-based or III-V/Si hybrid solutions introduce considerable complexity,

power consumption, or process integration risk. Rectangular and apodized Bragg gratings relax some of these constraints but still rely on sharp corners.

In contrast, the proposed sinusoidal DSBR + $\pi/2$ cavity achieves a favorable and well-balanced combination of metrics: an experimentally validated linewidth of ~ 0.25 nm ($Q \approx 6200$), an extinction ratio of ~ 22 dB, and a fiber-to-fiber insertion loss of 4–5 dB that is dominated by the grating couplers rather than the filter core. This performance is obtained within a compact footprint of only ~ 48 μm DSBR per side plus a single-period cavity, using a simple in-line waveguide geometry without separate bus/drop waveguides or sub-100-nm coupling gaps. The smooth sinusoidal sidewalls reduce high-spatial-frequency scattering and make the device less sensitive to lithographic and etch imperfections than rectangular gratings or tightly coupled ring-based structures, supporting good repeatability across devices on the same chip. Taken together, these characteristics indicate that the proposed DSBR filter offers a practically attractive point in the design space—combining single-line spectral response, compactness, low intrinsic loss, and CMOS-compatible fabrication—making it a strong candidate for integration in dense WDM links, precision sensing platforms, and emerging quantum and microwave photonic circuits. The resonance wavelength of the proposed filter is not actively tunable. The device is realized as a fully passive, fabricated structure, and no additional tuning elements—such as thermo-optic heaters, carrier injection/depletion regions, graphene layers, or other refractive-index modulation schemes—are integrated into the platform. As a result, the resonance wavelength is uniquely determined by the engineered geometry (including the grating period, duty cycle, and cavity length) together with the intrinsic material refractive indices. These parameters were rigorously optimized at the design stage to obtain a narrowband spectral response centered at 1550 nm with a maximized quality factor. It is worth noting that, in principle, the same platform could be extended to support active wavelength tuning by incorporating standard photonic tuning mechanisms (e.g., localized microheaters or p–n junctions); however, such developments lie beyond the scope of the present work and are deferred to future studies.

The reported characteristics stem from a strictly passive device configuration, in which the resonance wavelength is rigorously defined by the fabricated geometry and remains fixed, as no thermo-optic heaters, carrier injection/depletion regions, graphene overlays, or other refractive-index modulation mechanisms are incorporated into the platform. While some previously reported filters achieve higher values of individual performance metrics, they often do so at the cost of increased structural complexity or fabrication challenges. The proposed architecture instead offers a balanced combination of high spectral selectivity, compact in-line geometry, fabrication-friendly design, CMOS compatibility, and experimentally validated performance, making it well suited for practical integrated photonic applications. The proposed narrowband transmission filter is particularly suitable for DWDM, where the single isolated resonance enables high channel selectivity while suppressing adjacent-channel crosstalk. In

precision optical sensing, a narrow resonance linewidth enhances wavelength-interrogation accuracy, improving sensitivity to environmental perturbations such as refractive-index or temperature variations. The compact in-line architecture is also attractive for microwave photonic signal processing, where narrow optical filtering is required for high-selectivity RF filtering and sideband selection. Furthermore, the absence of sub-100-nm coupling gaps and the compact CMOS-compatible implementation make the proposed filter a promising building block for large-scale photonic integrated circuits and integrated quantum photonic routing.

The narrow defect-mode transmission window can be regarded as EIT-like in its spectral form because a narrow transmission feature appears inside the broader Bragg rejection band. In the present device, however, this behavior is produced by resonant tunneling through the localized defect mode of the $\pi/2$ phase-shifted Bragg cavity rather than by atomic coherence. Specific application scenarios include wavelength-selective channel filtering and add/drop functions in DWDM links, where the isolated transmission window can select a desired wavelength channel while rejecting adjacent wavelengths; optical carrier or sideband selection in microwave-photonic links, where narrow optical filtering can support high-selectivity RF signal processing; and wavelength-interrogated sensing, where small temperature- or refractive-index-induced resonance shifts can be tracked against the narrow transmission feature. The compact in-line response is also relevant to integrated photonic routing whenever a single narrow spectral channel must be transmitted through a broader rejection band.

Although the measured extinction ratio of approximately 22 dB and fiber-to-fiber insertion loss of approximately 4–5 dB do not represent record values among recently reported integrated filters, they demonstrate the effective filtering operation of the proposed architecture. It should be noted that the insertion loss is a system-level parameter mainly influenced by the input and output grating couplers, rather than solely by the Bragg resonator itself. In contrast, independent measurements of sinusoidal Bragg sections fabricated on the same SOI platform indicate intrinsic propagation losses of approximately 2.45–4.6 dB/cm, confirming the low excess propagation loss associated with the sinusoidal modulation. The measured insertion loss can be further reduced by improving the coupling interfaces, for example, through advanced grating-coupler designs such as apodized or focusing couplers, or by employing low-loss edge-coupling approaches.

VI. CONCLUSION

In this work, we have demonstrated the design, fabrication, numerical analysis, and experimental validation of a high- Q optical filter on an SOI platform using perturbed sinusoidal Bragg gratings. By incorporating a central $\pi/2$ phase-shifted cavity and carefully optimized sinusoidal sidewall modulation, the device achieved a transmission linewidth of 0.25 nm at 1550 nm, corresponding to a Q -factor of approximately 6200. This performance demonstrates the effectiveness of sinusoidal modulation in suppressing sidelobes and minimizing scattering losses. The FDTD simulations and experimental measurements

TABLE I
COMPARISON OF REPRESENTATIVE SOI NARROWBAND FILTERS. WBG-BASED FILTERS ARE LISTED FIRST FOR DIRECT BENCHMARKING; OTHER INTEGRATED FILTER ARCHITECTURES ARE INCLUDED FOR ARCHITECTURAL REFERENCE.

Filter Type	$\Delta\lambda$ (nm)	Q	ER (dB)	IL (dB)	Footprint / Length	Profile / Mechanism	Key Limitations	Ref.
Waveguide Bragg Grating (WBG)-Based Filters								
Rectangular sidewall WBG	0.20–0.40	3000–8000	15–25	4–6	100–300 μm	Binary corrugation	High spatial-frequency components; increased scattering; sidelobe leakage	[49], [50]
Phase-shifted rectangular WBG	0.10–0.30	5000–12000	20–30	3–5	150–300 μm	Binary + phase defect	Sensitive to phase errors; fabrication tolerance limits	[33]
Apodized WBG	0.05–0.20	8000–15000	25–35	3–6	200–400 μm	Apodized multi-level	Larger footprint; mask complexity; tight etch control required	[20], [23]
Subwavelength WBG	0.10–0.25	3000–10000	15–30	3–6	100–250 μm	SWG-engineered	High lithography sensitivity; dispersion engineering required	[4]
Contra-directional WBG	0.10–0.30	3000–10000	20–40	4–7	200–500 μm	Coupled-waveguide grating	Phase-matching sensitivity; routing complexity	[26], [51]
This work: sinusoidal DSB + $\pi/2$ cavity	0.25	≈ 6200	22	4–5	48 μm per reflector	Smooth sinusoidal modulation	Reduced scattering; compact in-line geometry; no sub-100-nm gaps; experimentally validated	This work
Other Representative SOI Narrowband Filters (Architectural Comparison)								
Microring resonator	0.02–0.10	10^3 – 10^4	15–30	3–6	10–60 μm radius	Evanescence coupling	Multiple FSR resonances; sub-100-nm gap sensitivity; thermal drift	[30]
Ring-assisted MZI	0.05–0.20	10^3 – 10^4	25–40	4–8	200–600 μm	Interference + resonator	Phase balancing required; increased circuit complexity	[24]
Photonic crystal cavity	< 0.02	$> 10^4$ (sim.)	20–30	3–6	10–30 μm	Band-edge localization	Extremely fabrication sensitive; disorder-induced Q degradation	[52]
Plasmonic filter	0.20–1.00	10^2 – 10^3	10–20	High	< 10 μm	Metal resonance	High intrinsic loss; limited Q; not CMOS-efficient	[4]

exhibited strong agreement, confirming that the numerical model reliably predicts the spectral characteristics of the fabricated device. The results also highlight the impact of practical coupling elements, as grating couplers introduce measurable insertion losses absent in the intrinsic filter response. By isolating these effects, the intrinsic narrowband filtering functionality of the design was verified with high fidelity. The demonstrated device combines narrow linewidth, high extinction ratio, and low insertion loss, making it a strong candidate for advanced applications in DWDM, microwave photonics, optical sensing, and emerging quantum photonic circuits. The compatibility of the design with CMOS nanofabrication further ensures scalability and integration with other photonic building blocks. Future work will explore thermal and electro-optical tuning mechanisms to extend the functionality of the device and enable dynamic reconfigurability for next-generation photonic systems.

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Kambiz Moez (S'01–M'07–SM'12) received his B.Sc. degree in electrical engineering from the University of Tehran, Iran, in 1999, and his M.Sc. and Ph.D. degrees from the University of Waterloo, Waterloo, Ontario, Canada, in 2002 and 2006, respectively. Since January 2007, he has been with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada, where he is currently a Professor and Associate Dean of Undergraduate Students—ECE. His research interests include the analysis and design of analog, radio-frequency, and millimeter-wave CMOS integrated circuits and systems for a variety of applications, including wired/wireless communications and sensors, radio-frequency energy harvesting, biomedical imaging, instrumentation, radars, and power electronics. He has authored or co-authored over 120 peer-reviewed journal articles and conference papers in his field of research. Dr. Moez is a Registered Professional Engineer in the province of Alberta. Dr. Moez served as Associate Editor for *IEEE Transactions on Circuits and Systems I: Regular Papers* from 2021 to 2023. He is currently serving as an Associate Editor for *IET Electronics Letters*.



Hamed Saghaei received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering in 2004, 2007, and 2015, respectively. He is currently a Guest Researcher with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada. His research interests span a broad range of photonic and electromagnetic technologies, with particular emphasis on silicon photonic integrated circuits, optical fibers, graphene-based photonic devices, and energy-harvesting technologies, including next-generation solar cells. His

research encompasses the design, numerical modeling, optimization, experimental characterization, and optical measurement of compact and high-performance photonic devices for applications in optical communications, sensing, and signal processing. Dr. Saghaei serves as a Topical Editor for the *Journal of the Optical Society of America B (JOSA B)* and has authored numerous peer-reviewed publications in optics, photonics, and applied electromagnetics.