

Article

Mode Discrimination in Quasi-PT-Symmetric Surface-Emitting DFB Semiconductor Lasers with Separated Gain and Radiating-Grating Sections

Haiyang Ji ^{1,2}, Yang Chen ^{1,2}, Guangliang Sun ^{1,2}, Ziyuan Liao ^{1,2}, Yunzhi Zhu ^{1,2}, Yongtao Wu ^{1,2}, Yufei Wang ^{1,3,*} and Wanhua Zheng ^{1,2,3,4,5,*}

¹ Laboratory of Solid State Optoelectronics Information Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

² Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

³ College of Future Technology, University of Chinese Academy of Sciences, Beijing 101408, China

⁴ Weifang Academy of Advanced Opto-Electronic Circuits, Weifang 261021, China

⁵ State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

* Correspondence: yufeiwang@semi.ac.cn (Y.W.); whzheng@semi.ac.cn (W.Z.)

Abstract

Surface-emitting distributed-feedback (SE-DFB) semiconductor lasers based on second-order gratings face a fundamental triple constraint: the spatial co-location of gain, grating feedback, and vertical radiation functions limits single-mode selectivity, surface extraction efficiency, and far-field beam quality simultaneously. We propose a quasi-parity-time (PT)-symmetric SE-DFB laser with separated gain and radiating-grating sections. In this design, the electrically injected gain section and the passive second-order grating section are placed in different regions along the cavity axis, thereby separating electrical injection from surface emission without epitaxial regrowth. Coupled-mode theory and two-dimensional finite-element simulations demonstrate that the resulting longitudinal non-Hermitian gain-loss asymmetry produces spatial-overlap-dependent threshold discrimination, enabling an isolated low-threshold lasing branch that remains separated from competing cavity modes over the investigated pump-parameter range. Under the HR-AR boundary condition, the proposed design achieves a threshold gain margin of $\Delta g = 12.4 \text{ cm}^{-1}$, more than six times that of a conventional HR-AR DFB benchmark considered here, together with an upward surface extraction efficiency of 23.4% obtained from 2D FEM simulations. A simplified steady-state rate-equation estimate further suggests that the increased threshold margin can support strong side-mode suppression. The design imposes no regrowth requirement and is fully compatible with standard single-growth InP ridge-waveguide fabrication.

Keywords: surface-emitting DFB laser; quasi-parity-time symmetry; non-Hermitian photonics; gain-guided mode discrimination; coupled-mode theory; second-order grating; semiconductor laser



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1. Introduction

Surface-emitting distributed-feedback (SE-DFB) semiconductor lasers based on second-order distributed-feedback gratings exploit the first-order diffraction of a second-order grating to achieve vertical surface emission in InP-compatible semiconductor platforms [1]. Compared with vertical-cavity surface-emitting lasers [2,3], SE-DFB lasers offer a narrower

emission linewidth [4], a smaller far-field divergence angle [5,6], a higher surface damage threshold [7], and a broader accessible wavelength range [8], making them attractive for coherent optical communications [9,10], high-resolution LiDAR [8], silicon photonics integration [11,12], and free-space sensing [4]. Fabricating the grating directly on a ridge waveguide eliminates the need for epitaxial regrowth and allows precise control of the grating coupling coefficient [13]. To avoid optical absorption by metal ohmic contacts deposited over the grating, electrodes are typically placed on the lateral sidewalls of the ridge [14], simultaneously improving contact quality and reducing device series resistance.

Despite these advantages, the practical realization of high-performance SE-DFB lasers is constrained by three competing requirements. First, metal contacts placed directly over the grating introduce absorption losses that suppress vertical extraction efficiency [13], and circumventing this through oxide-aperture confinement [10], non-injected DBR sections [15], or regrowth-based buried-grating platforms substantially increases fabrication complexity and thermal resistance [16,17]. Second, the full-aperture emission geometry of a uniform SE-DFB cavity produces a far-field beam with a longitudinal divergence well below one degree and a lateral divergence exceeding ten degrees [18], yielding a highly asymmetric spot that limits fiber-coupling efficiency [12]. Third, the two degenerate Bragg modes of a uniform second-order grating retain equal threshold gains under symmetric boundary conditions [5], making the device susceptible to antisymmetric-mode excitation and dual-lobe far-field splitting [19]. A $\lambda/4$ phase shift can lift the modal degeneracy but introduces a localized photon-density peak that drives spatial hole burning at elevated injection, degrading single-mode stability [4,10,20].

Non-Hermitian photonics, and in particular parity-time (PT) symmetry theory [21–24], offers an alternative mode-control framework beyond conventional phase-shift or regrowth-based designs. Introduced by Bender and co-workers in 1998 [25], PT symmetry requires the complex refractive index to satisfy $n(x) = n^*(-x)$ [26], pairing a gain region with a geometrically mirror-imaged loss region [27]. PT-symmetric and complex-coupled gratings have also been investigated in DFB laser cavities. Kulishov et al. proposed resonant DFB/DBR cavities based on unidirectional PT-symmetric diffractive gratings, while Zhu et al. showed through modal-gain analysis that PT-symmetric grating DFB lasers can provide stronger mode discrimination and improved robustness against facet-reflection uncertainty than conventional DFB lasers [28,29]. More recently, Benisty et al. analyzed design rules and facet effects in practical 1550 nm PT-symmetric grating DFB laser diodes, and Brac de la Perrière et al. experimentally demonstrated electrically injected complex-coupled DFB laser diodes with single-frequency operation, asymmetric amplification, and improved tolerance to optical feedback [30,31].

These PT-symmetric or complex-coupled DFB lasers provide important references for non-Hermitian mode control in DFB cavities. However, they mainly rely on periodic gain–loss modulation or complex grating design along the cavity axis [28,32,33]. Such periodic modulation usually requires patterned electrodes or carefully designed complex gratings, and the reported devices are primarily edge-emitting DFB lasers rather than second-order surface-emitting DFB lasers [34]. Therefore, they do not directly address the simultaneous requirements of surface extraction, radiating-aperture control, and removal of metal-contact absorption over the grating in SE-DFB lasers. Furthermore, applying transverse PT symmetry in an SE-DFB geometry would require a loss layer above the active region [24,35], reintroducing the metal-contact absorption the device is designed to avoid. Table 1 compares these PT-symmetric or complex-coupled DFB lasers with the present SE-DFB design, with emphasis on device function and fabrication requirements.

Table 1. Comparison of PT-DFB implementations and the present SE-DFB architecture.

Work	Main Mechanism	Implementation/Fabrication Feature	Difference from This Work
Kulishov et al. [28]	PT-symmetric diffractive grating in a DFB/DBR cavity	Theoretical grating-based cavity; no electrical-injection design	No SE-DFB surface extraction or separated gain/radiating-grating sections
Zhu et al. [29]	Modal-gain analysis of PT-symmetric grating DFB lasers	Periodic gain–loss modulation along the DFB cavity	Edge-emitting DFB; no passive radiating grating for surface emission
Benisty et al. [30]	PT-symmetric or complex-coupled grating design rules	Periodic complex grating/ gain–loss modulation	Edge-emitting complex grating; no second-order surface-emitting function
Brac de la Perrière et al. [31]	Electrically injected complex-coupled DFB laser	Complex grating and periodic gain–loss design	Edge-emitting DFB; no gain–radiation separation for SE-DFB
This work	Section-separated gain and passive radiating grating	No periodic electrodes; no epitaxial regrowth; metal contact kept away from the grating	SE-DFB with mode discrimination, vertical extraction, and gain–radiation separation

We address these limitations using a quasi-PT-symmetric SE-DFB laser in which the electrically pumped gain section and the passive second-order grating section are separated along the cavity axis. This gain–grating separation replaces periodic gain–loss modulation and simultaneously addresses mode selection, surface extraction, and far-field shaping: it keeps the metal contact away from the radiating grating, thereby reducing metal-related absorption loss; it confines the surface-emitting aperture to the passive grating section, reducing the longitudinal–transverse divergence mismatch; and it introduces a non-Hermitian gain–loss distribution that produces asymmetric modal thresholds without using a conventional $\lambda/4$ phase-shift section or epitaxial regrowth. Coupled-mode theory and two-dimensional finite-element simulations show that, under the HR–AR boundary condition, the proposed design provides a substantially increased threshold gain margin compared with the conventional HR–AR and $\lambda/4$ phase-shift DFB benchmarks considered in this work. A rate-equation estimate based on this threshold margin further suggests the potential for a high side-mode suppression ratio. The paper is organized as follows: Section 2 presents the device structure and theoretical model; Section 3 reports the AR–AR and HR–AR simulation results; Section 4 analyzes vertical extraction and far-field characteristics; and Section 5 concludes with design guidelines and practical considerations.

2. Device Structure and Physical Model

2.1. Device Architecture and Physical Model

The proposed quasi-PT-symmetric SE-DFB laser consists of a monolithic InP ridge-waveguide cavity with a total length $L = L_g + L_p$ [Figure 1]. Along the cavity axis, the device comprises an electrically injected active gain section and a passive second-order grating section. The gain-section length is defined as $L_g = N_{\text{gain}}\Lambda + l_{\text{shift}}$, where $N_{\text{gain}}\Lambda$ is the period-matched gain length and l_{shift} is the phase-adjustment length introduced at the gain–grating interface. The active section provides optical amplification and carries the metal ohmic contact, while the surface grating is confined to the passive section. The passive section has a length $L_p = N_{\text{slot}}\Lambda$ and contains an etched second-order InP slot grating that provides distributed feedback and vertical radiation coupling, without electrical injection. The ridge waveguide is designed for the C-band Bragg wavelength $\lambda_B = 1550$ nm.

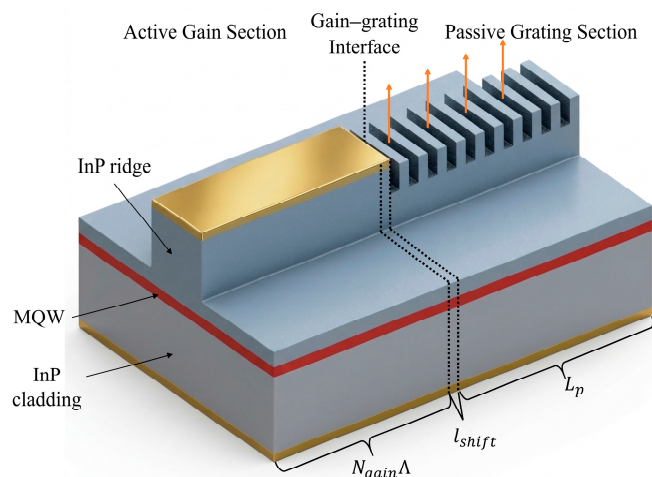


Figure 1. Three-dimensional schematic of the SE-DFB laser with longitudinally separated gain and radiating-grating sections. The monolithic InP ridge-waveguide cavity has a total length $L = L_g + L_p$, where the electrically injected active gain section is defined as $L_g = N_{\text{gain}}\Lambda + l_{\text{shift}}$. Here, l_{shift} denotes the phase-adjustment length introduced at the gain–grating interface. The passive section has a length L_p and contains the second-order surface grating for distributed feedback and vertical radiation. Metal ohmic contacts are confined to the surface of the gain section. The schematic is not drawn to scale; l_{shift} and the grating periods are enlarged for clarity.

By confining electrical injection to the gain section, metal ohmic contacts are kept away from the radiating aperture, eliminating contact absorption over the grating. In our model, the gain and absorption terms are applied to the MQW active region rather than to the surface grating. The pumped part of the MQW region provides optical gain, while the unpumped part remains absorptive because no carrier injection is supplied there. The second-order surface grating, etched in the upper waveguide/cladding region, is treated separately as the feedback and vertical-radiation element of the SE-DFB cavity, and is not included in the active-region PT index setting. The corresponding active-layer complex refractive index is written as:

$$n_{\text{act}}(z) = \begin{cases} n_{\text{act},0} + i\frac{\alpha_{\text{abs}}}{2k_0}, & 0 \leq z \leq L_p \\ n_{\text{act},0} + \Delta n_c(N, T) - i\frac{g}{2k_0}, & L_p \leq z \leq L_p + L_g \end{cases} \quad (1)$$

where $k_0 = 2\pi/\lambda_B$, $n_{\text{act},0} = 3.2827$ is the reference real refractive index of the active layer, g is the material gain in the electrically pumped section, and α_{abs} denotes the absorption or equivalent loss in the unpumped active region. The term $\Delta n_c(N, T)$ represents the carrier- and temperature-induced real-index change in the pumped section.

A strict PT-symmetric optical system requires the complex refractive index to satisfy $n(z) = n^*(-z)$, namely an even real part and an odd imaginary part. The present device is therefore referred to as quasi-PT-symmetric rather than strictly PT-symmetric, because the carrier-induced real-index change is not mirror-symmetric, the gain and loss magnitudes are not necessarily balanced, and the passive grating section also introduces radiation loss through the surface-emission channel. In practical electrically injected semiconductor lasers, the exact PT condition is difficult to satisfy because carrier-induced index changes, residual absorption, radiation channels, asymmetric facet feedback, and fabrication constraints generally disturb the ideal gain–loss balance. Therefore, PT and quasi-PT concepts in semiconductor lasers are often implemented through gain–loss engineering for mode control under realistic device conditions, rather than through an exact point-by-point refractive-index symmetry of the full finite cavity [33,36]. Although these deviations relax the exact PT condition, the opposite signs of the imaginary refractive index in the pumped

and unpumped parts of the MQW active region still provide a non-Hermitian gain–loss distribution that supports mode-pair evolution and mode localization.

In this quasi-PT configuration, the design rationale is to convert the separation of gain and radiation loss into modal threshold discrimination. The passive second-order grating is not only a spectral filter; it also acts as a distributed radiation-loss channel. Therefore, different longitudinal modes experience different effective gain–loss balances depending on their spatial overlap with the pumped gain section and the passive radiating grating section. A mode with stronger overlap with the pumped section reaches threshold at a lower threshold gain, whereas modes with larger overlap with the passive radiating grating section require higher gain. The resulting threshold gain margin is therefore produced by the combined action of Bragg feedback, vertical-radiation loss, and the separated gain–loss distribution, rather than by ordinary grating filtering alone.

Within this approximation, in the FEM threshold calculation, electrical injection is represented by varying the imaginary part of the active-region refractive index, while the real part is kept fixed. The carrier-induced real-index change is not solved self-consistently in the present cold-cavity model. Its main effect is to introduce an additional resonance detuning and phase shift, which may slightly change the absolute eigenfrequencies and threshold values but does not remove the gain/loss contrast imposed between the pumped and unpumped active regions.

The phase-adjustment length l_{shift} controls the phase relation between the field accumulated in the gain section and the Bloch amplitudes in the passive grating section. In the transfer-matrix analysis, l_{shift} is treated as a design parameter and optimized to maximize the threshold gain margin between the dominant lasing mode and the nearest competing mode, as discussed in Sections 3.1 and 3.2.

2.2. Grating Design and Parameter Optimization

The second-order grating in the passive section is realized as a periodic array of surface slots etched into the InP ridge. The grating period is set by the second-order Bragg condition:

$$\Lambda = \frac{m\lambda_B}{2n_{\text{eff}}} = \frac{\lambda_B}{n_{\text{eff}}}, m = 2, \quad (2)$$

where n_{eff} is the modal effective index of the guided mode used for the Bragg-period design. It should not be confused with the active-layer material refractive index $n_{\text{act},0}$ in Equation (1). For C-band operation near 1.55 μm , the calculated modal effective index is approximately 3.20, giving $\Lambda \approx 484$ nm. This second-order grating provides in-plane distributed feedback and first-order vertical diffraction for surface emission.

Two parameters are jointly optimized: the slot duty cycle, which controls the ratio of in-plane coupling coefficient κ to vertical radiation loss α_{rad} , and the number of grating periods N , which sets the trade-off between spectral selectivity and peak reflectivity saturation [Figure 2]. At the selected design point, $N_{\text{slot}} = 350$, $d_s = 0.24$ μm , and $h_2 = 1.35$ μm . The SMM calculation gives the main feedback feature near 1.548 μm , close to the finite-cavity eigenmode wavelength obtained from the FEM calculation. The extracted grating parameters are

$$\alpha_{\text{rad}} = 8.20 \text{ cm}^{-1}, \kappa = 6.67 \text{ cm}^{-1}, \quad (3)$$

yielding a stopband FWHM of 1.83 nm and a peak grating reflectivity of approximately 0.9%. The resulting passive section length is $L_p = N\Lambda = 350 \times 484 \text{ nm} = 169.4$ μm .

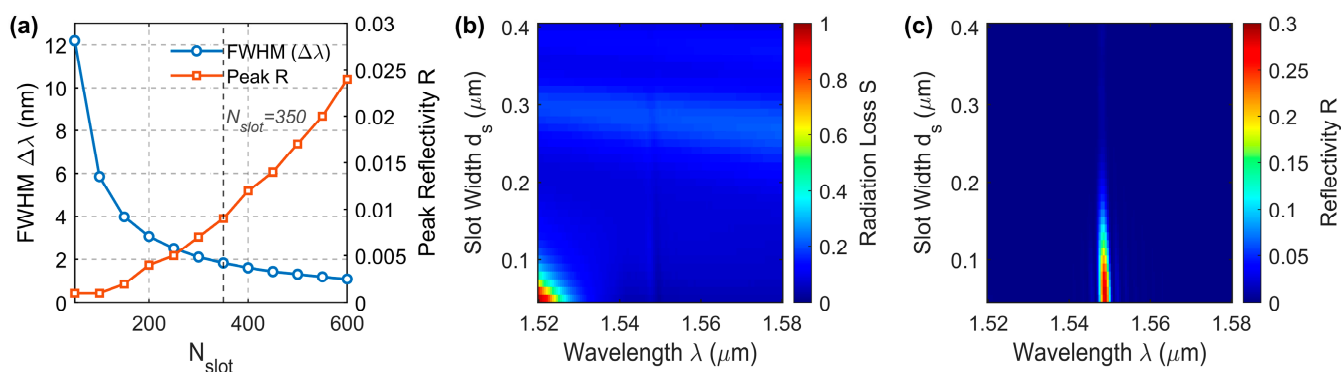


Figure 2. (a) Stopband FWHM and peak reflectivity as functions of grating period number N_{slot} . The dashed line indicates the design point at $N_{\text{slot}} = 350$. (b) Radiation loss S and (c) power reflectivity R as functions of wavelength and slot width d_s , calculated for $h_2 = 1.35 \mu\text{m}$ and $N_{\text{slot}} = 350$.

2.3. Coupled-Mode Theory and Threshold Analysis

The field evolution along the cavity is described by coupled-mode equations for the forward and backward Bloch amplitudes $A^+(\xi)$ and $A^-(\xi)$. Here, ξ is an auxiliary coordinate used only in the transfer-matrix calculation; it runs from the gain-side facet to the grating-side facet, with $\xi = 0$ at the gain-side facet and $\xi = L$ at the grating-side facet. The field vector is defined as

$$\mathbf{a}(\xi) = \begin{bmatrix} A^+(\xi) \\ A^-(\xi) \end{bmatrix}. \quad (4)$$

For a uniform section j , the coupled-mode equations are written as

$$\frac{d\mathbf{a}}{d\xi} = \begin{bmatrix} q_j & i\kappa_j \\ -i\kappa_j^* & -q_j \end{bmatrix} \mathbf{a}, \quad q_j = \frac{g_j - \alpha_j}{2} - i\delta_m. \quad (5)$$

Here, g_j and α_j are the intensity gain and loss coefficients assigned to section j . The factor $1/2$ appears because the equations are written for field amplitudes. In the present CMT/TMM calculation, the background internal loss in the pumped section is not introduced as a separate parameter; instead, g_0 is defined as the net intensity gain parameter used in the threshold scan.

The detuning term $\delta_m = \beta_m - \beta_B$ is the propagation-constant detuning of the m -th longitudinal mode from the Bragg condition, where $\beta_B = \frac{m\pi}{\Lambda} = \frac{2\pi n_{\text{eff}}}{\lambda_B}$.

For the second-order grating used here, $m = 2$. Thus, δ_m has units of inverse length, the same as κ_j , and is not a normalized detuning. Near the Bragg frequency, $\delta_m \simeq \frac{n_g}{c}(\omega_m - \omega_B)$, where n_g is the group index. In general, κ_j may be complex, with a phase determined by the grating origin and by the phase convention of A^+ and A^- . For the passive index-coupled InP slot grating considered here, this phase is absorbed into the Bloch-amplitude definitions, and κ is taken as a real positive coefficient in the transfer-matrix calculation.

In the electrically pumped gain section, $\kappa_g = 0$, $g_g = g_0$, $\alpha_g = 0$, so that

$$M_{\text{gain}} = \begin{bmatrix} e^{q_g L_g} & 0 \\ 0 & e^{-q_g L_g} \end{bmatrix}, \quad q_g = \frac{g_0}{2} - i\delta_m. \quad (6)$$

Here, g_0 is the net intensity gain parameter assigned to the pumped section.

In the passive grating section, no electrical gain is supplied. The section parameters are $g_p = 0$, $\alpha_p = \alpha_{\text{rad}}$, $\kappa_p = \kappa$, where α_{rad} is the equivalent vertical-radiation loss of the second-order surface grating. If absorption in the unpumped active region is included, it

can be added to α_p ; in the present CMT/TMM calculation, this additional absorption term is not introduced. With

$$q_p = -\frac{\alpha_p}{2} - i\delta_m, \gamma_p = \sqrt{q_p^2 + |\kappa|^2}, \quad (7)$$

the passive-grating transfer matrix is obtained from the standard coupled-wave formulation for DFB lasers [37]:

$$M_{\text{grat}} = \begin{bmatrix} \cosh(\gamma_p L_p) + \frac{q_p}{\gamma_p} \sinh(\gamma_p L_p) & \frac{i\kappa}{\gamma_p} \sinh(\gamma_p L_p) \\ -\frac{i\kappa^*}{\gamma_p} \sinh(\gamma_p L_p) & \cosh(\gamma_p L_p) - \frac{q_p}{\gamma_p} \sinh(\gamma_p L_p) \end{bmatrix}. \quad (8)$$

The phase-adjustment length l_{shift} is introduced at the gain-grating transition to tune the phase relation between the gain section and the passive grating section. Its transfer matrix is

$$M_{\text{shift}} = \begin{bmatrix} e^{-i\beta_B l_{\text{shift}}} & 0 \\ 0 & e^{i\beta_B l_{\text{shift}}} \end{bmatrix}. \quad (9)$$

For the final design evaluated here, $l_{\text{shift}} = 0$, and therefore M_{shift} reduces to the identity matrix. The total transfer matrix along the auxiliary coordinate ξ is

$$M_{\text{total}} = M_{\text{grat}} M_{\text{shift}} M_{\text{gain}} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}. \quad (10)$$

At the internal interfaces, the amplitude vector is taken to be continuous, so the section matrices are multiplied directly in the calculation order from the gain-side facet to the grating-side facet. The facet boundary conditions are applied only at the two cavity ends. The grating-side facet is anti-reflection coated, giving the outgoing-wave condition $A^-(\xi = L) = 0$.

For the AR-AR cavity, the gain-side facet also satisfies $A^+(\xi = 0) = 0$, which leads to the threshold condition

$$M_{22} = 0. \quad (11)$$

For the HR-AR cavity, the gain-side facet is described by the complex field-amplitude reflectivity r_{HR} , so that $A^+(\xi = 0) = r_{\text{HR}} A^-(\xi = 0)$, giving

$$M_{21} r_{\text{HR}} + M_{22} = 0. \quad (12)$$

The roots of Equations (11) and (12) in the (δ_m, g_0) plane give the longitudinal modes and their threshold gains [37].

The threshold gain margin is defined as:

$$\Delta g = g_{\text{th},2} - g_{\text{th},1}, \quad (13)$$

where $g_{\text{th},1}$ and $g_{\text{th},2}$ are obtained by sorting the threshold roots by increasing g_0 . The lowest-threshold root defines the dominant lasing mode, and the next-lowest root in the same spectral window defines the nearest competing side mode. Throughout the CMT/TMM analysis, g_0 denotes the scanned net gain parameter in the pumped section, g_{th} denotes a threshold gain obtained from the threshold equation, and Δg denotes the difference between the two lowest threshold gains.

2.4. Finite-Element Method Simulation Framework

The composite cavity was further analyzed using a two-dimensional FEM eigenfrequency model implemented in COMSOL Multiphysics 5.4. The simulation was performed

in the longitudinal-vertical (z , y) cross section using the out-of-plane electric-field component E_z . The passive grating section explicitly included $N_{\text{slot}} = 350$ etched slots with $\Lambda = 484$ nm, $d_s = 242$ nm, and $h_2 = 1.35$ μm , corresponding to $L_p = 169.4$ μm . The gain section was modeled as a uniform ridge-waveguide segment without surface corrugation.

The HR facet was implemented using a perfect electric conductor boundary condition, whereas the AR facet was modeled using a scattering boundary condition. Top and bottom Cartesian PMLs with polynomial coordinate stretching and a thickness of (0.8 μm) were used to absorb vertically radiated fields. The near-field data for the far-field calculation were sampled on a line in the physical air region immediately before the top PML. The mesh was locally refined near the grating slots and active core: the slot boundaries and adjacent high-index-contrast regions used a typical maximum element size of (60–80 nm), while the active core used a maximum element size of approximately (78 nm). Coarser elements were used in the remote air, cladding, and substrate regions. Moderate mesh changes did not alter the relevant modal ordering or threshold-crossing behavior.

The refractive index was assigned in COMSOL using the convention that a negative imaginary part represents optical gain, whereas a positive imaginary part represents material loss. Accordingly, the active-layer index in the electrically injected gain section was set to $n_{\text{gain}} = 3.2827 - in_i$, where $n_i > 0$ was swept to represent increasing gain under electrical injection. The corresponding material intensity gain coefficient is $g_{\text{mat}} = 2k_0n_i = 4\pi n_i/\lambda_B$, which is used only to convert the FEM imaginary-index sweep to material gain. In the unpumped section containing the surface grating, the active-layer index was set to $n_{\text{loss}} = 3.2827 + i \times 0.001$ to account for residual material absorption in the unpumped active layer. This fixed imaginary part corresponds to $\alpha_{\text{abs}} \approx 81$ cm^{-1} at $\lambda_B = 1550$ nm before modal-confinement weighting. The vertical radiation loss of the second-order grating is included through the radiating geometry and PML boundaries in the FEM eigenfrequency calculation, and is therefore not included in this material absorption term.

The CMT/TMM and FEM models therefore treat the passive-section loss at different levels of approximation. In the CMT/TMM model, the passive grating is represented by the effective parameters κ and α_{rad} , and the residual absorption of the unpumped MQW region is not included separately. In the FEM model, the grating radiation loss is included by the actual radiating structure and PML boundaries, while n_{loss} accounts for the residual absorption of the unpumped active layer. Therefore, the two models are compared mainly in terms of modal ordering, threshold separation, and the mode-discrimination mechanism, rather than exact equality of absolute threshold values.

The remaining layer indices were kept identical to those stated in Section 2.1. Complex eigenfrequencies $f = f_r + if_i$ were extracted directly. Under the eigenfrequency sign convention used in this work, $f_i > 0$ corresponds to temporal decay and $f_i < 0$ corresponds to net growth; therefore, the lasing threshold of each modal branch was identified from the zero-net-growth condition $f_i = 0$.

3. Mode Discrimination Analysis: AR–AR and HR–AR Configurations

3.1. Modal Analysis of the AR–AR Configuration

Without a phase-shift region ($l_{\text{shift}} = 0$), the dominant lasing mode reaches threshold at $n_{i,\text{th}} = 0.0112$, while the nearest competing mode crosses threshold at $n_{i,\text{th}} = 0.0124$, yielding a relative threshold margin of only 10.7%. A parametric sweep of l_{shift} under the AR–AR threshold condition [Equation (11)] identifies an optimal value of $l_{\text{shift,opt}} = 217.8$ nm [Figure 3], at which the imaginary-frequency separation between Lasing 3 and its nearest competitor increases by 20% at $n_i = 0.010$, modestly improving the threshold margin to 11.6% [Figure 4b]. This improvement is fundamentally limited by the open-cavity bound-

any condition itself: without end-facet reflection, all modes share comparable round-trip gain requirements, leaving little room for intra-cavity phase adjustment to differentiate between them.

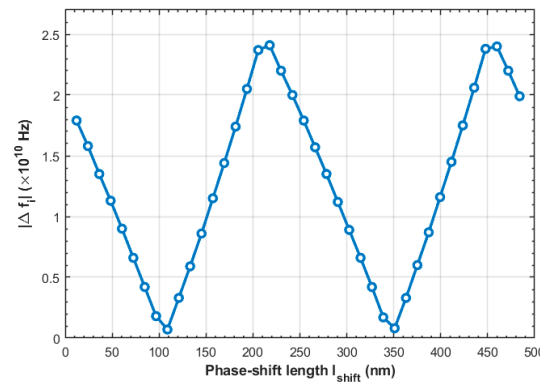


Figure 3. Imaginary-frequency separation $|\Delta f_i|$ between the two lowest-threshold modes as a function of the phase-shift section length l_{shift} , calculated for an AR–AR cavity with $L_g = L_p = 169.4 \mu\text{m}$, $N_{\text{slot}} = 350$, and $h_2 = 1.35 \mu\text{m}$. The periodic dependence arises from the round-trip phase accumulation within the composite cavity. A maximum mode discrimination of $2.4 \times 10^{10} \text{ Hz}$ is achieved at the optimal phase-shift length $l_{\text{shift}} = 217.8 \text{ nm}$.

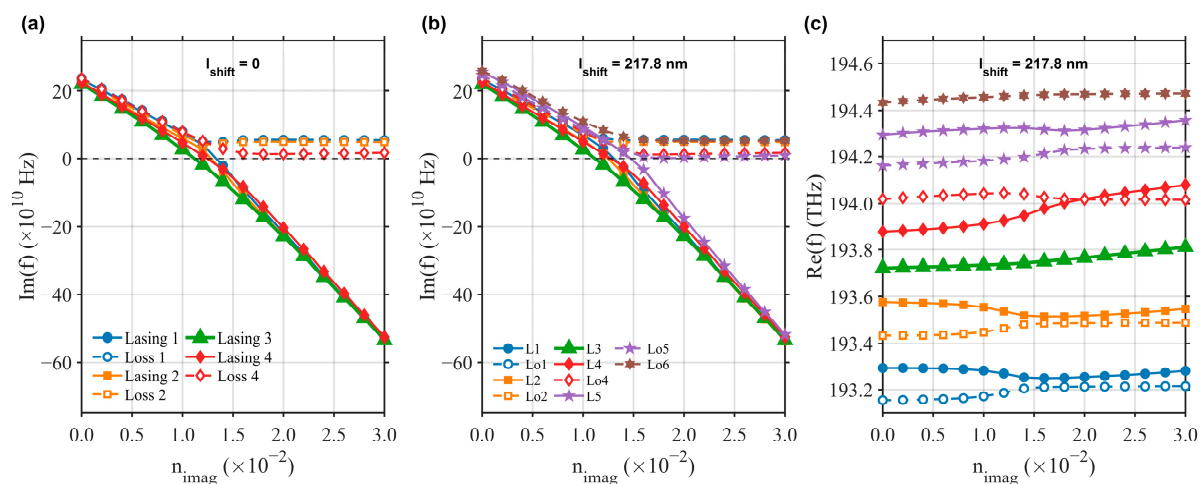


Figure 4. Mode evolution in the AR–AR quasi-PT composite cavity. (a) Imaginary parts of the complex eigenfrequencies at $l_{\text{shift}} = 0$. The zero crossing of $\text{Im}(f)$ defines the threshold under the eigenfrequency convention used in this work. The primary mode L3 (bold green) reaches threshold at $n_{\text{imag}} = 0.0112$, maintaining a 10.7% threshold margin over the nearest competitor L4. (b) Imaginary eigenfrequencies at optimal phase shift ($l_{\text{shift}} = 217.8 \text{ nm}$). The mode separation at $n_{\text{imag}} = 0.010$ increases by 20%, modestly improving the threshold margin to 11.6%. (c) Real eigenfrequencies for $l_{\text{shift}} = 217.8 \text{ nm}$. Several competing mode pairs show frequency convergence, whereas L3 remains an isolated branch within the scanned range.

FEM eigenfrequency analysis under $l_{\text{shift}} = 217.8 \text{ nm}$ tracks ten cavity modes, which are organized into four pairs and one isolated mode [Figure 4b,c]. Several higher-order competing mode pairs show real-frequency convergence and imaginary-part separation as injection increases, with each loss-mode partner remaining above threshold throughout $n_i \in [0, 0.030]$. In contrast, the dominant lasing mode L3 follows an isolated trajectory within the scanned range, without an unambiguous partner branch, avoided crossing, or exceptional-point (EP) signature. Its lower threshold arises from its stronger spatial overlap with the electrically pumped gain section and weaker overlap with the passive radiating grating section. Near the L3 threshold ($n_i = 0.012$), the longitudinal field distribution

reveals that L3 concentrates 81.5% of its energy within the gain section, while the nearest competing mode (L2) distributes only 30.2% of its energy there [Figure 5]. These complementary energy distributions explain the threshold margin. The differential gain-section confinement $\Delta\Gamma_z = 0.815 - 0.302 = 0.513$ allows L3 to extract gain more efficiently, whereas L2 overlaps more strongly with the passive radiating grating section. This differential spatial overlap constitutes the non-Hermitian gain-guided mode-discrimination mechanism. The resulting 11.6% relative threshold margin under AR–AR conditions is nonetheless limited by the open-cavity boundary condition, as discussed below.

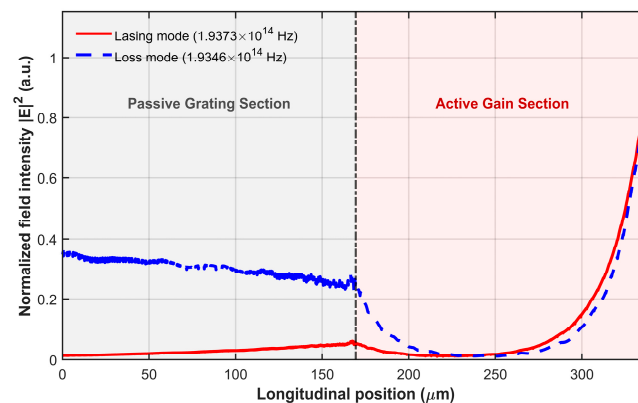


Figure 5. Normalized longitudinal field intensity profiles $|E|^2$ of the lasing mode and the competing loss mode for the AR–AR cavity with $l_{\text{shift}} = 217.8$ nm and $n_i = 0.012$. Each profile is normalized to its own maximum value. The lasing mode is predominantly confined in the active gain section (right), while the loss mode extends into the passive grating section (left), resulting in a large threshold gain difference Δg_{th} .

Despite this favorable mode structure, the AR–AR configuration is not viable for practical operation: the absence of end-facet feedback raises the lasing threshold to $n_{i,\text{th}} = 0.0112$, approximately $3.3\times$ above the HR–AR case (as shown in Section 3.2). The AR–AR analysis nonetheless establishes two key results carried forward to Section 3.2: the feasibility of improving the threshold gain margin through phase-adjustment length optimization, and the non-Hermitian spatial-overlap mechanism that produces mode-dependent threshold discrimination.

3.2. Modal Analysis of the HR–AR Configuration

Introducing a high-reflection (HR) coating on the gain-section facet reduces end-facet transmission loss and modifies the feedback phase of the finite cavity. This boundary condition should be distinguished from the quasi-PT description used in this work, which refers to the internal non-Hermitian gain–loss distribution formed by the electrically pumped gain section and the passive radiating grating section. The HR coating does not create the gain–loss asymmetry; instead, it enhances the threshold separation produced by this internal gain–loss distribution. Under the HR–AR boundary condition [Equation (12)], a parametric sweep reveals that the threshold gain margin Δg undergoes periodic oscillation as the cleave position varies [Figure 6]. The intrinsic spatial separation of the quasi-PT structure ensures that the dominant mode maintains a lower lasing threshold than all competing modes across a broad phase interval, with $|\Delta f_i|$ reaching its local maxima of 1.08×10^{10} Hz near $l_{\text{shift}} = 217.8$ nm and 459.8 nm. The value at $l_{\text{shift}} = 0$ nm is comparable to these maxima and falls within a fabrication tolerance window of approximately ± 50 nm, making it the preferred design point as it eliminates the need for precision phase-trimming at the gain-grating interface. This tolerance arises because the mode discrimination is distributed

over the separated gain and passive grating sections, rather than being concentrated at a single $\lambda/4$ phase-shift position.

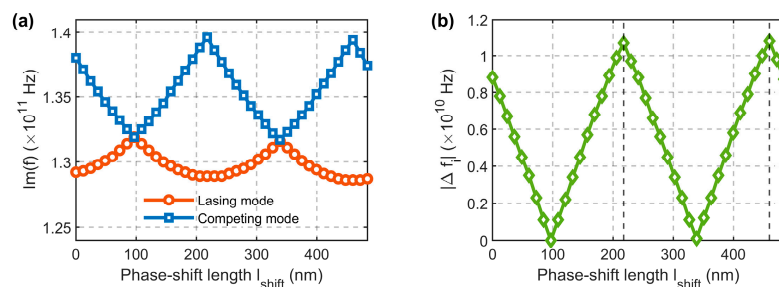


Figure 6. Phase-shift tolerance analysis for the HR-AR cavity configuration. (a) Imaginary parts of the eigenfrequencies of the lasing mode and the competing mode as functions of the phase-shift length l_{shift} . (b) Imaginary-frequency separation $|\Delta f_i|$ vs. l_{shift} . Two optimal operating points at $l_{\text{shift}} = 217.8 \text{ nm}$ and 459.8 nm yield maximum mode discrimination within one grating period.

The CMT transfer-matrix analysis under HR-AR conditions [Equation (12)] tracks the complex eigenfrequencies of the two lowest-threshold stopband modes as material gain g_0 increases from zero. The dominant lasing mode reaches threshold at $g_{\text{th},1} \approx 70 \text{ cm}^{-1}$, while the nearest competing mode does not reach threshold until $g_{\text{th},2} \approx 82 \text{ cm}^{-1}$, yielding:

$$\Delta g = g_{\text{th},2} - g_{\text{th},1} = 12.4 \text{ cm}^{-1}. \quad (14)$$

This result is also obtained from a global TMM root search in the (δ_m, g_0) plane, which extracts $g_{\text{th}} = 69.94 \text{ cm}^{-1}$ and 82.28 cm^{-1} for the two modes, in good agreement with the CMT result. To benchmark the proposed design against conventional SE-DFB structures, we also evaluated a uniform HR-AR SE-DFB and a conventional $\lambda/4$ phase-shifted SE-DFB using the same total cavity length, grating period, grating-period number, coupling coefficient, radiation loss, HR reflectivity, and spectral search window. For the $\lambda/4$ phase-shifted benchmark, the phase shift was placed at the cavity center, and the facet phase was not separately optimized. The uniform HR-AR DFB yields $\Delta g \approx 2 \text{ cm}^{-1}$, while a $\lambda/4$ phase-shift design provides $\Delta g \approx 4\text{--}8 \text{ cm}^{-1}$. In comparison, the proposed quasi-PT HR-AR design gives $\Delta g = 12.4 \text{ cm}^{-1}$, indicating a larger threshold-based mode-discrimination margin without requiring a $\lambda/4$ phase-shift section, epitaxial regrowth, or precision phase trimming at the gain-grating transition.

The physical origin of this mode discrimination is different from that of a conventional $\lambda/4$ phase-shifted DFB laser. In a $\lambda/4$ phase-shifted cavity, the phase shift acts as a localized phase defect that selects a defect resonance and lifts the Bragg-mode degeneracy. The selected mode is therefore usually associated with enhanced photon density near the phase-shift position. In the present design, no localized $\lambda/4$ phase defect is introduced. Instead, the threshold separation is produced by the gain-loss distribution between the electrically pumped gain section and the passive radiating-grating section. Modes with stronger overlap with the pumped section reach threshold at lower gain, whereas modes with larger overlap with the passive grating section experience stronger radiation loss and require higher gain. Therefore, the proposed structure provides mode discrimination through the separated gain and radiating-grating sections, rather than through a localized phase-shift defect.

Based on this threshold-gain margin, we further estimated the side-mode suppression ratio (SMSR) using a steady-state side-mode rate-equation approximation. The SMSR value is therefore not extracted directly from the linear FEM eigenfrequency calculation. In this

model, gain clamping by the dominant lasing mode suppresses the nearest side-mode photon density. For the side mode, the steady-state photon density can be approximated as

$$S_s \approx \frac{\beta_{sp} R_{sp}}{v_g \Delta g}, \quad (15)$$

where S_s is the side-mode photon density, β_{sp} is the spontaneous-emission coupling factor into the side mode, R_{sp} is the spontaneous-emission recombination rate, v_g is the group velocity, and Δg is the threshold gain margin between the dominant mode and the nearest competing side mode. Using $R_{sp} = BN_{th}^2$, the SMSR can be written as

$$\text{SMSR} = 10 \log_{10} \left(\frac{S_m}{S_s} \right) = 10 \log_{10} \left(\frac{v_g \Delta g S_m}{\beta_{sp} B N_{th}^2} \right), \quad (16)$$

where S_m is the photon density of the dominant lasing mode, B is the bimolecular radiative recombination coefficient, and N_{th} is the threshold carrier density. Using representative parameters for C-band InP-based quantum-well lasers,

$$\begin{aligned} v_g &= 8.33 \times 10^9 \text{ cm s}^{-1}, \Delta g = 12.4 \text{ cm}^{-1}, \\ S_m &= 10^{15} \text{ cm}^{-3}, \beta_{sp} = 2.2 \times 10^{-5}, \\ B &= 10^{-10} \text{ cm}^3 \text{ s}^{-1}, N_{th} = 2 \times 10^{18} \text{ cm}^{-3}, \end{aligned}$$

the estimated SMSR is

$$\text{SMSR} = 10 \log_{10} \left[\frac{8.33 \times 10^9 \times 12.4 \times 10^{15}}{2.2 \times 10^{-5} \times 10^{-10} \times (2 \times 10^{18})^2} \right] \approx 40.7 \text{ dB}. \quad (17)$$

Here, v_g corresponds to a group index of approximately 3.6, Δg is obtained from the CMT/TMM threshold analysis, and the remaining parameters are typical values used for InP-based semiconductor-laser estimates. This value should be regarded as a rate-equation estimate based on the calculated threshold gain separation. It is not a direct output of the FEM eigenfrequency calculation. In an experimental device, the measured SMSR may be lower because of gain compression, carrier diffusion, spatial hole burning, thermal effects, and residual facet-phase uncertainty.

FEM eigenfrequency analysis under $l_{\text{shift}} = 0$ nm tracks six cavity modes comprising three lasing modes and three lossy modes [Figure 7]. The dominant lasing mode reaches threshold at $n_{i,\text{th}} = 0.0034$, while the nearest competing mode does not cross threshold until $n_{i,\text{th}} = 0.0055$, yielding a 61.8% relative threshold margin, which is $5.8\times$ larger than that obtained in the AR–AR case. As in Section 3.1, the dominant lasing branch remains isolated within the scanned range $n_i \in [0, 0.030]$, without a clearly identifiable partner branch, frequency coalescence, avoided crossing, or EP signature. Its lower threshold is attributed to the spatial gain–loss overlap of the competing modes with the electrically pumped gain section and the passive radiating grating section under the HR–AR boundary condition.

Near the lasing threshold ($n_i = 0.004$), the HR boundary reconstructs the cavity field from a unidirectional traveling-wave distribution into a standing-wave envelope centered at the gain-grating interface ($z = 169.4 \mu\text{m}$) [Figure 8]. Spatial integration of $|E(z)|^2$ shows that 56.3% of the dominant mode energy redistributes into the passive grating section at $n_i = 0.004$ —substantially increasing photon density over the radiating aperture relative to the AR–AR case—while 43.7% is retained in the gain section. The competing lasing mode, by contrast, concentrates 68.2% of its energy in the grating section and only 31.8% in the gain section. This difference in gain-section overlap contributes to the threshold gain margin of 12.4 cm^{-1} , together with the Bragg feedback, vertical-radiation loss, and HR–AR

boundary condition. At high injection ($n_i = 0.024$), the dominant mode maintains a smooth field envelope within the gain section without a pronounced localized intensity peak. This distribution suggests a reduced tendency toward field-localization-induced spatial hole burning compared with conventional $\lambda/4$ phase-shift designs; however, quantitative evaluation of spatial hole burning requires an above-threshold model including gain saturation, carrier transport, and thermal feedback.

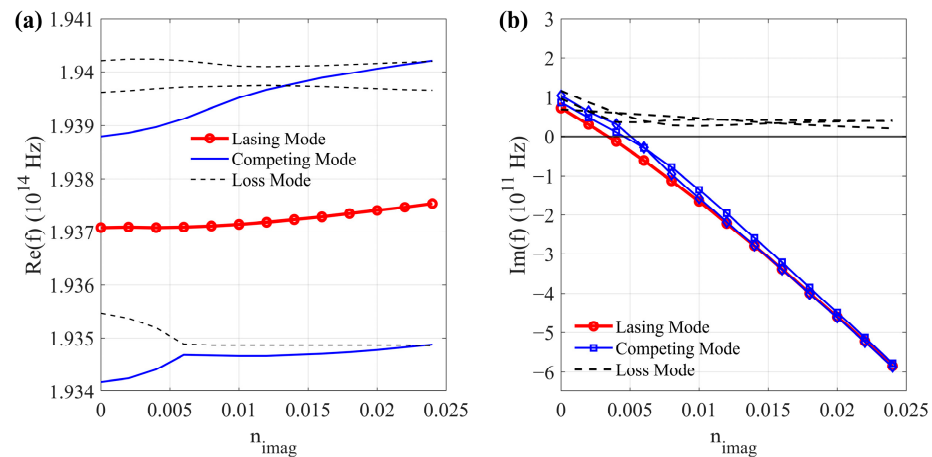


Figure 7. Complex eigenfrequency evolution of six modes in the HR-AR quasi-PT cavity ($l_{\text{shift}} = 0$) vs. n_{imag} . (a) Real eigenfrequencies showing frequency convergence of lasing–loss pairs. (b) Imaginary eigenfrequencies relative to the lasing threshold (dashed line). The dominant lasing mode (red) reaches threshold at $n_{\text{imag}} = 0.0034$, maintaining a 61.8% margin over competing modes (blue). All loss modes (black dashed) remain suppressed ($\text{Im}(f) > 0$) throughout the range, indicating improved single-mode discrimination.

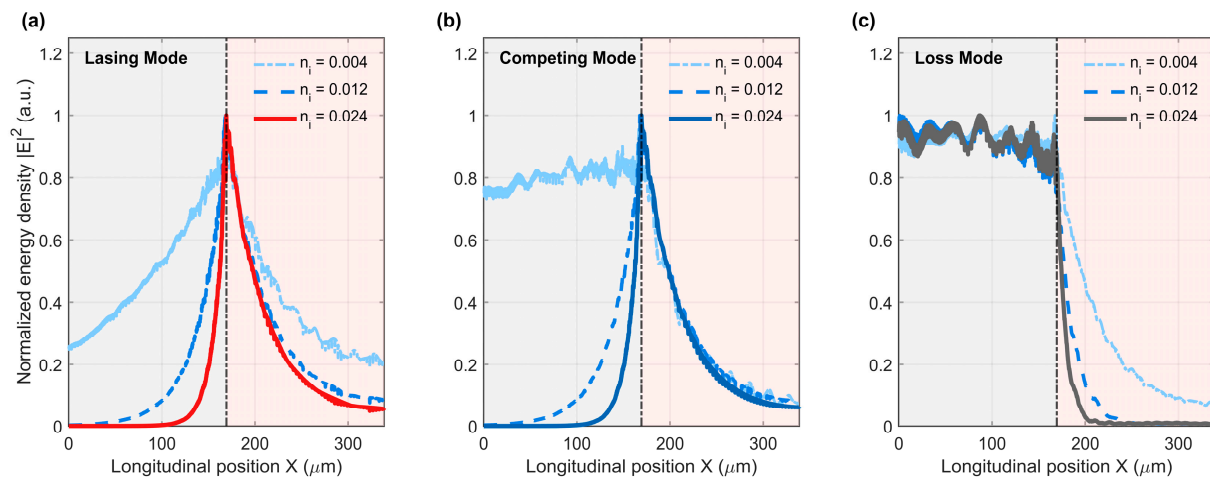


Figure 8. Normalized longitudinal field intensity profiles $|E(z)|^2$ for the HR-AR quasi-PT cavity ($l_{\text{shift}} = 0$) at various n_{imag} . Gray and pink areas represent the passive grating and active gain sections, respectively. (a) Lasing mode: progressive localization toward the HR gain facet without a pronounced localized intensity peak. (b) Competing mode: energy remains predominantly in the passive section, leading to a higher threshold. (c) Loss mode: over 94% energy concentration in the grating section at $n_{\text{imag}} = 0.024$, indicating stronger overlap with the passive radiating grating section.

4. Vertical Emission and Far-Field Characteristics

Beyond threshold-based mode discrimination, the proposed cavity should also maintain efficient surface emission from the second-order grating. We therefore evaluate the vertical extraction efficiency and far-field pattern in this section. These quantities are standard SE-DFB performance metrics, but in the present structure they are affected by the

quasi-PT gain–loss distribution because it reshapes the selected-mode field envelope over the passive radiating grating section. Since this grating section is the only surface-emitting aperture, its field distribution determines both the extraction efficiency and the longitudinal far-field profile.

4.1. Surface Extraction Efficiency

The upward extraction efficiency η_{up} is calculated from the time-averaged Poynting-vector flux of the FEM eigenmode. The upward-emitted power P_{up} is obtained by integrating $\langle \mathbf{S} \rangle \cdot \hat{\mathbf{n}}$ over the top boundary in the physical air region before the PML, where $\langle \mathbf{S} \rangle = \frac{1}{2} \text{Re}(\mathbf{E} \times \mathbf{H}^*)$. The total radiated power is obtained from all open radiation and leakage channels, $P_{\text{total}} = P_{\text{up}} + P_{\text{down}} + P_{\text{HR}} + P_{\text{AR}}$, and the upward extraction efficiency is defined as $\eta_{\text{up}} = \frac{P_{\text{up}}}{P_{\text{total}}}$. This quantity describes the optical radiative power partition in the 2D FEM model and should not be interpreted as the electrical-to-optical efficiency of a complete device.

Under the AR–AR configuration, the dominant mode at threshold ($n_i = 0.012$) yields $\eta_{\text{up}} = 0.13\%$; the absence of end-facet feedback causes the field to propagate predominantly as a traveling wave toward the ungrated facet, diverting the majority of optical energy away from the passive grating aperture. Introducing the HR coating on the gain-section facet suppresses this end-facet leakage and forms a standing-wave-like field distribution that substantially increases the photon density over the grating region. In this 2D model, the primary lasing mode under HR–AR conditions reaches a peak $\eta_{\text{up}} = 23.4\%$ near $n_i = 0.012$ [Figure 9a], representing an approximately 180-fold enhancement over the AR–AR case. At higher injection levels, the fractional power balance shifts progressively toward substrate radiation [Figure 9b], indicating that substrate-side optical recycling represents a viable path to further efficiency improvement.

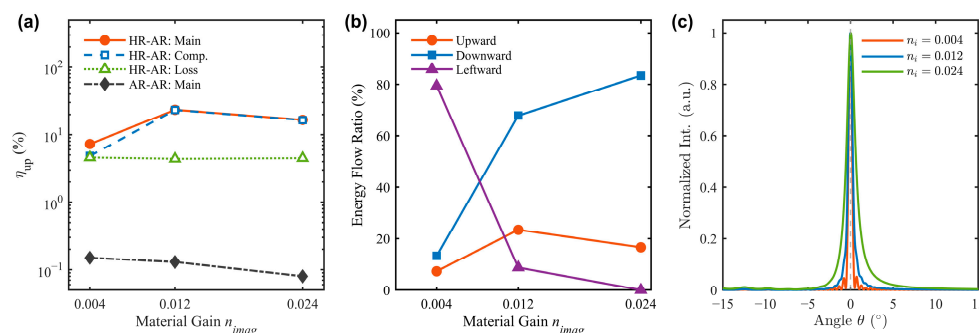


Figure 9. Vertical emission characteristics of the HR–AR quasi-PT cavity ($l_{\text{shift}} = 0$) vs. n_{imag} . (a) Surface extraction efficiency η_{up} (log scale) for tracked modes. The HR–AR primary mode peaks at 23.4% near $n_{\text{imag}} = 0.012$, representing a ~ 180 -fold enhancement over the AR–AR case. (b) Fractional power distribution among upward, downward (substrate), and leftward (HR leakage) channels. Increasing gain shifts the dominant energy flow from the HR facet toward the substrate. (c) Normalized longitudinal far-field patterns obtained from the 2D FEM model at three injection levels. The beam remains centered at $\theta = 0^\circ$ with a FWHM divergence of 0.47° – 1.19° , indicating stable beam pointing within the present linear eigenmode model.

4.2. Far-Field Characteristics

The longitudinal far-field intensity pattern is obtained by Fourier-transforming the near-field amplitude at the top boundary. As shown in Figure 9c, the beam remains centered at $\theta = 0^\circ$ over the investigated gain range, indicating stable beam pointing within the present linear eigenmode model. The longitudinal divergence (FWHM) narrows from 1.19° at low injection ($n_i = 0.004$) to 0.47° at high injection ($n_i = 0.024$), as the dominant-mode field progressively extends over the passive radiating grating.

The transverse far-field divergence is not directly resolved in the present 2D longitudinal-vertical FEM model. As a first-order estimate, for a single-mode InP ridge waveguide with $W_{\text{ridge}} = 3 \mu\text{m}$, the lateral mode radius can be approximated as $w_0 = W_{\text{ridge}}/2 = 1.5 \mu\text{m}$, giving

$$\theta_{\perp} = \frac{2\sqrt{\ln 2}\lambda_B}{\pi w_0} \approx 31.4^{\circ}. \quad (18)$$

Combining this value with the calculated longitudinal divergence of 0.47° – 1.19° gives $\eta_c = \theta_{\parallel}/\theta_{\perp} \approx 0.015$ – 0.038 . For a full-aperture SE-DFB with the same total cavity length, $\theta_{\parallel}$ would be approximately halved, giving $\eta_c \approx 0.008$ – 0.019 . Thus, the proposed aperture restriction reduces the longitudinal-transverse divergence mismatch but does not eliminate beam ellipticity. A full beam-quality prediction requires a three-dimensional model.

5. Conclusions

We have proposed and theoretically analyzed a quasi-PT-symmetric SE-DFB laser architecture in which the active gain section and the passive radiating-grating section are separated within a monolithic InP ridge-waveguide cavity. The design addresses three major constraints in conventional SE-DFB lasers. First, separating the electrical injection from the radiating grating removes metal-contact absorption from the emitting aperture. Second, the quasi-PT gain-loss distribution provides a threshold gain margin of $\Delta g = 12.4 \text{ cm}^{-1}$ under HR-AR boundary conditions, exceeding the conventional HR-AR and $\lambda/4$ phase-shifted benchmarks considered here without requiring a $\lambda/4$ phase-shift section, epitaxial regrowth, or precision phase trimming. Third, restricting the emission aperture to the passive grating section reduces the difference between the longitudinal and transverse far-field divergence compared with a full-aperture SE-DFB, although the estimated transverse divergence shows that the beam remains elliptical.

The HR-AR composite cavity raises the surface extraction efficiency from 0.13% to 23.4%, with a substantial fraction of the remaining power directed toward the substrate, suggesting that substrate-side optical recycling represents a viable path to further efficiency improvement. The zero-phase-shift design point ($l_{\text{shift}} = 0$) offers a fabrication tolerance window of approximately $\pm 50 \text{ nm}$ and requires no epitaxial regrowth, making the architecture fully compatible with standard single-growth InP ridge-waveguide processing. These results demonstrate that a quasi-PT SE-DFB design with separated gain and passive radiating-grating sections provides a practical route toward high-performance surface-emitting DFB semiconductor lasers.

6. Discussion

Several practical factors should be considered when transferring the proposed design to fabricated devices. The interface between the gain section and the passive grating section is not a regrown butt-joint or bonded material interface; it is the position where the top metal contact ends and the etched second-order grating starts in the same ridge waveguide. Therefore, the main non-idealities at this position are expected to be local scattering, residual reflection, etch-depth variation, and sidewall roughness near the first grating periods, rather than abrupt material discontinuity. The present FEM model includes the designed grating geometry, but random roughness and lithographic fluctuations are not considered. Therefore, the calculated threshold gain margin and extraction efficiency should be interpreted as design-level estimates for the specified geometry. The equal gain-grating length used in the baseline design is a representative balanced choice rather than an optimized global solution. Representative eigenfrequency sweeps show that a longer gain section lowers the first threshold but reduces the threshold margin and enhances

multimode competition, whereas a longer passive grating section improves modal filtering at the cost of a higher threshold. The near-equal partition was therefore selected to balance moderate threshold and non-Hermitian mode selectivity. A full partition-ratio optimization of extraction efficiency and far-field performance would require additional power-flow and far-field simulations and is beyond the scope of the present revision.

The HR–AR facet condition also affects the quantitative performance. The HR coating does not create the gain–loss asymmetry, which originates from the separation between the electrically pumped gain section and the passive radiating grating section. Instead, it reduces end-facet transmission loss and enhances the threshold separation produced by the non-Hermitian gain–loss distribution. In practical devices, finite HR reflectivity, residual AR reflection, coating phase errors, coating aging, lateral heat diffusion, and carrier leakage into the passive section may shift the absolute resonance frequencies and threshold gains. The phase-shift-length sweep gives a first-order estimate of the sensitivity to effective boundary-phase variations, but it does not replace a full coating-tolerance and fabrication-tolerance analysis.

Several modeling simplifications should also be noted. The material gain is represented by an effective imaginary-index change in the active MQW region, while self-consistent carrier transport, gain saturation, gain compression, carrier-induced real-index change, thermal feedback, spatial hole burning, and dynamic mode competition are not included. Therefore, the calculated threshold gain margin should be regarded as a threshold-based modal-selectivity metric rather than a complete proof of large-signal single-mode stability. The estimated SMSR is a parameter-dependent steady-state rate-equation estimate based on gain clamping by the dominant mode, not a direct result of the FEM eigenfrequency calculation. The FEM eigenfrequency analysis is two-dimensional and does not capture finite ridge-width effects, lateral current spreading, transverse mode competition, sidewall scattering, or full three-dimensional radiation. Therefore, the extraction efficiency, longitudinal far-field divergence, and estimated beam aspect ratio should be regarded as design estimates under the adopted 2D model. Further reduction in the longitudinal–transverse divergence mismatch would require lateral mode engineering, such as a wider ridge with single-transverse-mode control, lateral photonic-crystal filtering, or lateral gain–loss engineering. Full three-dimensional electromagnetic simulations, preferably coupled with carrier-transport, multimode carrier–photon, and thermal models, will be required for quantitative device optimization.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Anti-reflection
CMT	Coupled-mode theory
DFB	Distributed feedback
EP	Exceptional point
FEM	Finite-element method
FWHM	Full width at half maximum
HR	High reflection
MQW	Multiple quantum well
PML	Perfectly matched layer
PT	Parity-time
SE-DFB	Surface-emitting distributed-feedback
SHB	Spatial hole burning
SMM	Scattering-matrix method
SMSR	Side-mode suppression ratio
TMM	Transfer-matrix method

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