

**Investigation of InAs/InP Quantum-Dot/Dash
Materials for Fabry-Perot Lasers and VCSELs**

Gaowen Chen

A Thesis
In the Department
of
Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Electrical and Computer Engineering) at
Concordia University
Montreal, Quebec, Canada

February 2026

© Gaowen Chen, 2026

**CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES**

This is to certify that the thesis prepared

By: *Gaowen Chen*

Entitled: *Investigation of InAs/InP Quantum-Dot/Dash Materials for Fabry-Perot Lasers and VCSEs*

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (*Electrical and Computer Engineering*)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. Honghao Fu Chair

Dr. Karin Hinzer External Examiner

Dr. Pablo Bianucci Examiner

Dr. Geln Cowan Examiner

Dr. M. Zahangir Kabir Examiner

Dr. John Xiupu Zhang Thesis Supervisor

Approved by _____
Dr. Jun Cai, Graduate Program Director

April/22/2026 _____
Dr. Mourad Debbabi
Gina Cody School of Engineering & Computer Science

ABSTRACT

Investigation of Quantum-Dot/Dash Materials for Fabry-Perot Lasers and VCSELs

Gaowen Chen, Ph.D.
Concordia University, 2026

Quantum-dot (QD) and quantum-dash (Qdash) semiconductor lasers have attracted significant attention for optical communication and interconnect systems due to their discrete density of states, reduced linewidth enhancement factor, and improved temperature stability compared with conventional quantum-well devices. These advantages make them promising candidates for emerging applications such as wavelength-division multiplexing, optical frequency comb generation, and high-speed optical interconnects in co-packaged optics architectures. However, the performance of QD/Qdash lasers is strongly influenced by complex interactions between nanostructure morphology, strain distribution, carrier transport, and optical cavity dynamics. A comprehensive framework that links nanostructure-level physics to device-level performance remains an important research challenge.

This dissertation investigates the physics and device applications of QD and Qdash gain media for Fabry-Pérot lasers and vertical-cavity surface-emitting lasers (VCSELs). An integrated multi-physics simulation framework is developed to bridge electronic-structure modeling and dynamic laser behavior. The framework combines optical cavity eigenmode analysis, eight-band $k \cdot p$ electronic structure calculations, and travelling-wave time-domain (TDTW) carrier-photon dynamics, enabling self-consistent modeling of optical confinement, transition energies, dipole matrix elements, and carrier transport processes. Additional coupling mechanisms, including vertical stacking interactions and lateral carrier tunneling, are incorporated into the carrier dynamics to capture ensemble effects in densely packed nanostructure systems.

Using this framework, the dissertation first investigates vertical coupling effects in chirped stacked QD and Qdash active regions. It is shown that strain redistribution and electronic coupling between stacked layers strongly influence the distribution of optical transition energies. Depending on the stacking sequence, vertical coupling can either compress or expand the ensemble gain spectrum. Device-level simulations demonstrate that descending stacked structures enhance optical bandwidth and enable stable broadband mode-locking in Fabry–Pérot lasers without increasing the number of active layers.

The second part of the study focuses on lateral coupling effects in dense Qdash ensembles. By constructing a parallel Qdash pair model, the role of interdash tunneling in carrier redistribution is quantified. The results show that electron tunneling from higher-energy to lower-energy nanostructures can concentrate carriers into dominant gain states, leading to reduced threshold current in long-cavity Fabry–Pérot lasers. The impact of lateral coupling is found to depend strongly on device geometry and carrier density, highlighting the importance of morphology-aware device design.

Finally, coordinated bandgap and strain engineering strategies are investigated for high-speed C-band Qdash VCSELs. By introducing composition-engineered Qdashes and optimized confinement layers, emission wavelength control is decoupled from nanostructure height, enabling improved carrier confinement and enhanced differential gain. Time-domain simulations predict significant improvements in modulation bandwidth and large-signal eye-diagram performance compared with conventional Qdash VCSEL structures.

Overall, this dissertation establishes a physics-driven design framework linking nanostructure engineering, carrier dynamics, and optical cavity design in QD/Qdash semiconductor lasers. The results provide insights into coupling mechanisms in nanostructured gain media and demonstrate how these effects can be exploited to realize broadband, low-threshold, and high-speed laser devices for next-generation optical communication systems.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Professor John Xiupu Zhang, for his guidance, encouragement, and continuous support throughout my PhD study. His insight and patience have been invaluable to my research and professional development.

I am deeply grateful to my parents and my brother for their unconditional love, encouragement, and constant support during this journey.

I would also like to thank Fujuan Huang for many valuable discussions and helpful suggestions that greatly benefited my research.

Finally, I would like to thank my friends Wenhao Yang, Ke Qiang, Jianzhao Gou, Hanqin Cao, and Chang Xu for the joyful and relaxing moments we shared during my PhD. Their friendship made this journey much more enjoyable.

Table of Contents

List of Figures	x
List of Acronyms.....	xvi
Chapter 1 Introduction	1
1.1 Development of Optical Interconnects and Telecommunication Systems.....	1
1.2 Semiconductor Laser Structures for Optical Communication Systems.....	3
1.3 Gain Media for Semiconductor Lasers: From Quantum Wells to Quantum Dots and Quantum Dashes	6
1.4 Laser Requirements for Co-Packaged Optics Systems.....	9
1.5 State of the Art in Qdot and Qdash Lasers.....	12
1.6 Overview of modeling Qdot/dash laser	18
1.7 Summary	19
Chapter 2 Problem Statement and Research Motivation	21
2.1 From Background to the Fundamental Design Challenge.....	21
2.2 Dense QD/Qdash Assemblies and Unavoidable Coupling Effects.....	23
2.3 Limitations of Existing Modeling Approaches	25
2.4 Research Motivation and Objectives	28
Chapter 3 Background Theory and Calculation Methods.....	30
3.1 Framework Overview and Design Philosophy	30
3.2 Laser cavity eigenmode analysis	32
3.3 Eight-band k.p model.....	35
3.3.1 Strain Distribution.....	35

3.3.2 Piezoelectric Potential.....	36
3.3.3 Electronic Band Structure	37
3.3.4 Light–Matter Interaction and Interband Transition Rate	41
3.4 Time-domain traveling wave model	44
3.4.1 Rate Equations for Qdash	49
3.4.2 TDTW model for single section mode-locked laser	51
3.4.3 TDTW model for Qdash VCSEL.....	52
3.4.4 Numerical Implementation of the TDTW Model	54
3.5 Model Validation.....	55
3.5.1 Validation of optical eigenmode analysis	55
3.5.2 Validation of eight-band k.p model.....	56
3.5.3 Validation of TDTW model	57
Chapter 4 Broad Emission Bandwidth Using Chirped QDot Structures	60
4.1 Introduction.....	60
4.2 Geometric Configuration of the Chirped QDot Structures	62
4.3 Optical Transition Energy of Isolated Quantum Dots.....	64
4.4 Vertical Strain Coupling in Chirped Stacked QDot	66
4.5 Optical Transition Energy in Chirped Stacked QDot.....	72
4.6 Performance of Single Section Mode-Lock Laser.....	75
4.7 Extension to Chirp Stacked QDash.....	79
4.8 Conclusions.....	82

Chapter 5 Threshold Reduction from Lateral Coupling Effects in InAs/InGaAsP Qdash Structures	84
5.1 Introduction.....	84
5.2 Geometry and Morphological Characteristics of InAs/InGaAsP Quantum Dashes	85
5.3 Electronic Structure of Isolated Quantum Dashes	88
5.4 Lateral Interdash Tunneling Mechanisms	92
5.5 Carrier Redistribution Induced by Lateral Tunneling	97
5.6 Influence of Lateral Coupling on Laser Threshold and Device Performance	100
5.7 Conclusions.....	104
Chapter 6 Composition and Strain Engineering of Qdash Active Regions for High-Speed C-Band VCSELs	106
6.1 Introduction.....	106
6.2 Wafer-Fused VCSEL Architecture and Optical Mode Characteristics	107
6.3 Bandgap and Strain Engineering for Emission Blue-Shifting	111
6.4 Confinement Enhancement and Optical Transition Strength.....	116
6.5 Static Laser Characteristics and Differential Gain Enhancement.....	119
6.6 Dynamic Modulation Performance and Bandwidth Enhancement.....	122
6.7 Conclusions.....	125
Chapter 7 Concluding Remarks	128
7.1 Summary	128
7.2 Recommendations for Future Work	130

Appendix.....	133
A.1 Material Parameters Used in the 8-band k-p Model Calculations at RT/LT	133
A.2 Main Parameters Used in the TDTW Models for F-P Laser.....	134
A.3 Main Parameters Used in the TDTW Models for VCSEL.....	135
References.....	136
Publications.....	154

List of Figures

Figure 1.1 Three semiconductor laser structures. [9]	3
Figure 1.2 Density of states for bulk structure, quantum well, quantum wire and quantum dot [19].....	6
Figure 1.3 AFM images of InAs/InP : (a) Qdot, (b) Qdash [28]	8
Figure 1.4 Evolution of optical interconnect architectures from copper DAC and pluggable optics to on-board optics, 2.5D CPO, chiplet-based CPO, and 3D CPO, illustrating progressively reduced electrical interconnect length and increasing system bandwidth beyond 100 Tb/s [32].....	10
Figure 1.5 Schematic illustration of dense wavelength division multiplexing (DWDM) for bidirectional optical communication, where multiple wavelength channels are multiplexed onto a single fiber and separated at the receiver using optical MUX/DEMUX devices [47].	13
Figure 1.6 Structural and optical characteristics of QDash and QDot laser devices. (a) SEM image of self-assembled quantum dashes. (b) SEM image of self-assembled quantum dots. (c) Cross-sectional SEM image of the fabricated ridge waveguide with a width of 2.3 μm . (d) Schematic layer structure of the QDash laser. (e) Measured optical frequency comb [57].	14
Figure 2.1 Net gain coefficient g versus applied current density, for the SOAs of three different gain mediums [77].	22
Figure 3.1 Schematic diagram of the unified simulation framework.	30
Figure 3.2 Schematic of carrier dynamics in a 4-level excitonic model of the active region of a typical QD laser [129].....	48
Figure 3.3 Schematic of carrier dynamics in lateral coupled Qdashes active region.	49
Figure 3.4 Sketch of calculation workflow of TDTW model [129].	54

Figure 3.5 Simulated transverse optical field intensity distributions for a 2.3 μm ridge-width Fabry–Pérot laser obtained from optical cavity eigenmode analysis. (a) Fundamental lateral mode showing strong confinement within the ridge core region. (b) First higher-order lateral mode exhibiting a split intensity profile with a central node and increased radiation leakage.	55
Figure 3.6 (a) Simulated time-domain pulse trains of a single-section mode-locked Fabry–Pérot laser for ascending and descending stacked active-region configurations. The repetition period is 10.8 ps, corresponding to a repetition frequency of approximately 92 GHz. The inset shows the simulated pulse shapes on a femtosecond timescale, with pulse widths of 164 fs and 135 fs for the two configurations. (b) Measured autocorrelation trace of the device, showing a pulse spacing of 10.81 ps [134], in excellent agreement with the simulated cavity round-trip time.	58
Figure 3.7 Simulated optical spectrum of the single-section mode-locked laser (descending stacked configuration), exhibiting a clear optical frequency comb with uniform mode spacing of 92 GHz.	59
Figure 4.1 Geometric structures: single QDot structure (left), and two chirped stacked structures (right). The numbers in the right figure indicate the QDot heights in nm. The ascending and descending chirped QDot structure are indicated in the left and right side, respectively.....	62
Figure 4.2 (a) The hydrostatic and biaxial strain distribution along vertical [001] direction; (b) the strained conduction band and valence band edges along [001] direction.....	64
Figure 4.3 Comparison of optical transition energies between calculation results (with $\pm 1.5\%$ error) and experimental data in [138].	66
Figure 4.4 The hydrostatic strain distribution along vertical [001] direction for ascending stacked with $T_c=10$ nm.....	67
Figure 4.5 The hydrostatic strain distribution along vertical [001] direction for descending stacked with $T_c=10$ nm.....	68

Figure 4.6 The hydrostatic strain distribution along vertical [001] direction for ascending stacked with $T_c=20$ nm.....	69
Figure 4.7 The strained conduction band and valence band edges along [001] direction for the ascending stacked with $T_c=10$ nm.....	70
Figure 4.8 The strained conduction band and valence band edges along [001] direction for the descending stacked with $T_c=10$ nm.....	71
Figure 4.9 The evolution of optical transition energies as a function of capping layer thickness T_c for ascending stacked structure.....	72
Figure 4.10 The evolution of optical transition energies as a function of capping layer thickness T_c for descending stacked structure.....	73
Figure 4.11 The probability density of lowest electron eigenstate for ascending and descending stacked structure at capping layer thickness of 10 and 15 nm, respectively.....	74
Figure 4.12 Laser performance under RT at injection current density of 880 A/cm ² : (a) the gain spectrum of ascending and descending structures.	76
Figure 4.13 Laser performance under RT at injection current density of 880 A/cm ² : (a) the optical spectrum for ascending stacked structure; and (b) the optical spectrum for descending stacked structure.....	77
Figure 4.14 (a) Optical spectrum -3-dB bandwidth as a function of injection current density; and (b) the number of -3-dB comb lines as a function of injection current density.	78
Figure 4.15 The bright exciton energy of target Qdash in ascending stacked structure; (b) in descending stacked structure; (c) the hydrostatic strain profile; (d) and (e) the optical spectrums.	80
Figure 5.1 Geometric structure: (a) isolated single quantum dash, (b) quantum dash pair. Quantum dash morphology statistical data: (c) length distribution, (d) width distribution, (e) adjacent Qdash distance.....	86

Figure 5.2 The change of Qdash ground state optical transition energy as function of Qdash width and length.....	88
Figure 5.3 The change of Qdash ground state optical transition energy as function of Qdash height.....	89
Figure 5.4 First 10 electron eigen states energy distribution change with Qdash length.	90
Figure 5.5 The evolution of the 3D probability density functions (PDFs) for electron states in Qdashes of lengths 75 nm and 300 nm.	91
Figure 5.6 Diagram of simulated Qdash pair.....	92
Figure 5.7 The change of ground-state electron PDFs overlap integral as function of (a) the height of the high-emission-energy Qdash and the interdash distance, (b) the width and the interdash distance.....	93
Figure 5.8 The 1D wave function along [0 -1 1] direction and 3D PDF visualizations for (d) strong coupling case, (e) weak coupling case.....	94
Figure 5.9 the same-shell tunneling time change with interdash distance.....	95
Figure 5.10 The change of heavy hole ground-state PDFs overlap integral as function of (a) the height of the high-emission-energy Qdash and the interdash distance, (b) the width and the interdash distance.....	96
Figure 5.11 The 1D wave function along [0 -1 1] direction and 3D PDF visualizations for (c) the same-shell (S-S) resonance, (e) hetero-shell (S-P) resonance.	97
Figure 5.12 The density of state occupation probabilities of Qdashes under fast and slow tunneling rates for F-P laser with a 1500 μm cavity.....	98
Figure 5.13 The P-I curves change with different tunneling rate for F-P laser with a 1500 μm cavity.....	100
Figure 5.14 P-I curves under fast and slow tunneling rates for F-P laser with different cavity lengths and $2\text{-}\lambda$ cavity VCSEL.	102

Figure 5.15 the density of state occupation probabilities of Qdashes under fast and slow tunneling rates for 2- λ cavity VCSEL.	103
Figure 6.1 Schematic of the wafer-fused C-band VCSEL structure.....	108
Figure 6.2 Material composition and geometric configuration of the InAs Qdash active region.	108
Figure 6.3 Optical characteristics of the VCSEL cavity: normalized longitudinal electric-field distribution, inset is standing-wave field pattern.	109
Figure 6.4 Optical characteristics of the VCSEL cavity: calculated optical confinement factor as a function of Qdash height.	110
Figure 6.5 Ground-state transition energy versus Qdash height for various capping layer compositions.	112
Figure 6.6 (a) Conduction band diagrams and (b) hydrostatic strain distributions comparing InP and InGa _{0.1} P _{0.9} FCLs.	113
Figure 6.7 Conduction band profile and hydrostatic strain distributions for the P-alloyed InAs _{0.95} P _{0.05} Qdash with 1.15Q and 1.10Q InGaAsP SCL.	114
Figure 6.8 Ground-state electron–hole probability density overlap versus Qdash height.	116
Figure 6.9 Cross-sectional ground-state electron probability density distributions. Top: same Qdash height with different FCL compositions. Bottom: same material composition with different Qdash heights.	117
Figure 6.10 Dipole lengths at 1550 nm for different Qdash configurations.	119
Figure 6.11 Static lasing performance calculated using the TDTW model. (a) P-I characteristics, (b) Lasing spectra.	120
Figure 6.12 Static lasing performance calculated using the TDTW model: Gain and differential gain versus wavelength at 7 mA injection current.	121

Figure 6.13 Dynamic modulation characteristics. Small-signal modulation response (S21) at various bias currents for (a) the baseline Qdash VCSEL and (b) the composition-engineered VCSEL..... 123

Figure 6.14 Large-signal NRZ eye-diagram Q-factor versus modulation frequency at 11 mA injection current, 10% modulation amplitude. Inserts are eye-diagrams at modulation frequency 40 Gbit/s..... 124

List of Acronyms

AFM	Atomic force microscopy
BTJ	Buried tunnel junction
CBE	Conduction band edge
CMOS	Complementary metal–oxide–semiconductor
CPO	Co-packaged optics
CWDM	Coarse wavelength-division multiplexing
CB	Conduction band
CBE	Conduction band edge
CW	Continuous-wave
CM	Continuum mechanical
DBR	Distributed Bragg reflector
DFB	Distributed feedback laser
DWDM	Dense wavelength-division multiplexing
EP	Empirical pseudopotential
ES	Excited state
FP	Fabry-pérot
FEM	Finite element method
FDTD	Finite-difference time-domain
FCL	First capping layer
FWHM	Full width at half magnitude
GS	Ground state
GVD	Group-velocity dispersion
IMDD	Intensity modulation / direct detection
I/O	Input/output

HH	Heavy-hole
LH	Light-hole
LT	Low temperature
MUX/DEMUX	Multiplexer/demultiplexer
NRZ	Non-return-to-zero
ODE	Ordinary differential equation
PAM4	Four-level pulse-amplitude modulation
PCSEL	Photonic-crystal surface-emitting laser
PDE	Partial differential equation
P-I	Power–current (curve/characteristic)
PIC	Photonic integrated circuits
PZT	Piezoelectric
PDF	Probability density function
BPM	Propagation method
Qdashe	Quantum dashe
QD	Quantum dot
QW	Quantum well
RIN	Relative intensity noise
RT	Room temperature
SCH	Separate confinement heterostructure
SCL	Second confinement layer
SEM	Scanning electron microscopy
SPM	Scanning probe microscopy
SO	Split-off
SK	Stranski-Krastanov
TCAD	Technology computer aided design

TB	Tight-binding
TDTW	Time-domain travelling-wave
VBE	Valence band edge
WDM	Wavelength-division-multiplexing
WL	Wetting layer

Chapter 1 Introduction

1.1 Development of Optical Interconnects and Telecommunication Systems

The rapid growth of global data traffic over the past two decades has fundamentally reshaped modern communication systems. Driven by cloud computing, artificial intelligence, and high-performance computing, networks are now required to deliver ever-increasing bandwidth under strict constraints on power consumption, latency, and scalability. As electrical interconnects struggle to meet signal integrity and energy-efficiency requirements at high data rates, optical communication technologies have become essential [1].

Within data centers, traffic patterns have shifted from predominantly north–south flows toward highly distributed east–west communication between servers, storage, and accelerators. This evolution has led to the widespread adoption of leaf–spine network architectures, which provide uniform bandwidth and predictable latency by densely interconnecting switches [2]. As a result, the number of optical links scale rapidly with system size, driving the deployment of short-reach optical interconnects in extremely large volumes. These links must therefore achieve high port density, low cost, and low power consumption while operating reliably in thermally constrained environments, placing stringent requirements on optical transmitters [3].

At the same time, increasing line rates have significantly tightened transceiver performance requirements. The transition from 100-Gb/s to 400-Gb/s and 800-Gb/s Ethernet has been enabled primarily by higher-order modulation formats such as four-level pulse-amplitude modulation (PAM4), combined with forward error correction. While PAM4 increases data throughput without raising symbol rates, it reduces noise margins and increases sensitivity to bandwidth limitations and noise. Consequently, laser sources must provide stable output power, low relative intensity noise, and sufficient modulation bandwidth to maintain signal integrity under increasingly constrained operating conditions [4].

Beyond short-reach interconnects, metro and long-haul telecommunication networks impose a different set of demands. Coherent optical communication has become the dominant approach for achieving high spectral efficiency over long distances by exploiting advanced digital signal processing. In coherent systems, the laser serves as both a light source and a phase reference, making linewidth, frequency stability, and phase noise critical parameters [5]. Recent advances have extended coherent technology into compact pluggable modules, enabling its adoption in data-center interconnect and metro applications.

Laser design is further influenced by the choice of operating wavelength. The O-band near 1310 nm aligns with the zero-dispersion region of standard single-mode fiber and is therefore widely used for short- and medium-reach links. In contrast, the C-band near 1550 nm offers minimum fiber attenuation and compatibility with erbium-doped fiber amplifiers, making it the preferred window for long-haul and amplified metro systems. These wavelength windows reflect fundamental trade-offs between dispersion, loss, and system complexity [6], [7].

From a system perspective, laser performance must be optimized across multiple, often competing, metrics. Sufficient output power is required to close the optical link, while low noise is essential for high-speed modulation. Temperature tolerance is increasingly important in high-density environments with limited cooling, and unavoidable reflections from facets and packaging interfaces make tolerance to optical feedback a key requirement. As data rates continue to increase, these constraints become more tightly coupled, complicating device optimization.

Energy efficiency has therefore emerged as a primary design consideration. To limit overall power consumption as aggregate bandwidth scales, trends such as co-packaged and on-board optics move optical conversion closer to electronic chips, reducing electrical losses. In these architectures, lasers must operate reliably in compact, thermally challenging packages while supporting high modulation speeds and standardized interfaces[8].

In summary, the evolution of optical interconnect and telecommunication systems has led to increasingly stringent and multifaceted requirements for semiconductor laser sources. Achieving

high bandwidth, low noise, stable wavelength operation, and robust thermal and feedback tolerance simultaneously—while remaining scalable and manufacturable—motivates continued exploration of advanced gain materials and laser architectures.

1.2 Semiconductor Laser Structures for Optical Communication Systems

Semiconductor lasers used in optical interconnect and telecommunication systems can be broadly categorized by their cavity configuration and feedback mechanism. While all such devices rely on stimulated emission within a semiconductor gain medium, differences in cavity geometry, optical confinement, and feedback control give rise to distinct performance characteristics and application domains. Understanding these structural differences is essential for appreciating why multiple laser architectures coexist in modern optical systems and why gain-medium design must be tailored to the target platform.

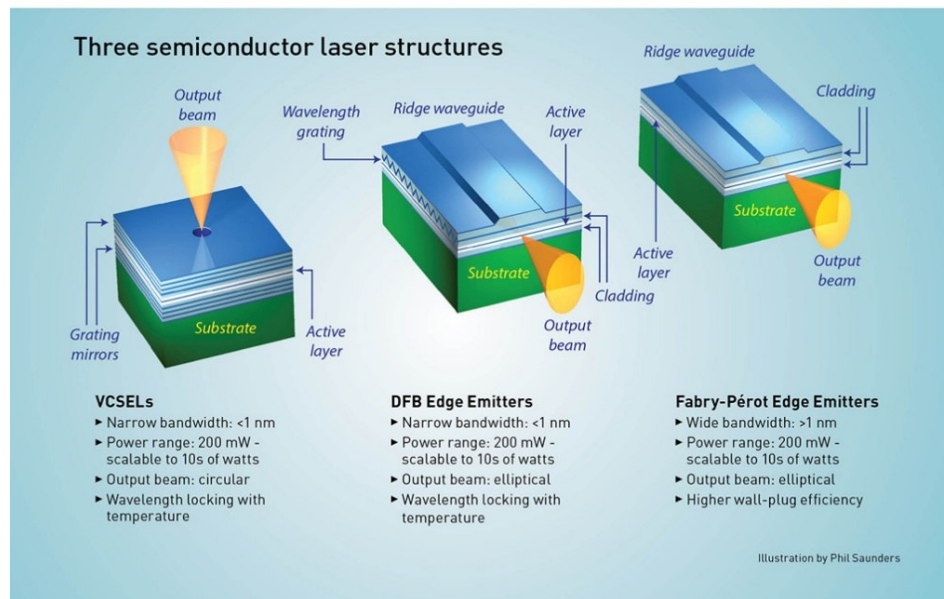


Figure 1.1 Three semiconductor laser structures.[9]

The most fundamental semiconductor laser structure is the Fabry–Perot (FP) edge-emitting laser, in which optical feedback is provided by reflections from the cleaved facets of a waveguide cavity. FP lasers are characterized by relatively simple fabrication, as they do not require wavelength-selective elements within the cavity. As a result, they are widely used as baseline

devices for material evaluation and as cost-effective light sources in applications where strict single-mode operation is not required. The longitudinal modes of FP lasers are determined by the cavity length, leading to multi-mode emission unless additional mode-control mechanisms are employed. In optical interconnects and certain broadband applications, this multi-mode behavior can be advantageous, particularly when combined with gain media that provide wide spectral coverage. Moreover, the comparatively large cavity volume and moderate optical confinement of FP lasers make them well suited for investigating gain-medium properties and carrier dynamics, as device behavior is strongly influenced by the intrinsic characteristics of the active region [10]. For applications requiring stable single-mode operation and precise wavelength control, distributed feedback (DFB) lasers are widely employed. In DFB lasers, a periodic grating is incorporated into the waveguide to provide wavelength-selective feedback, suppressing competing longitudinal modes and enforcing single-frequency emission. This architecture has become a cornerstone of telecommunication systems, particularly in wavelength-division multiplexed networks where channel spacing and wavelength stability are critical. DFB lasers offer narrow linewidth, high side-mode suppression ratio, and excellent spectral stability, making them suitable for both direct detection and coherent transmission systems [11]. However, the inclusion of a grating introduces additional fabrication complexity and tightens tolerances on material uniformity and refractive index control. Therefore, the interaction between the gain medium and the optical cavity becomes more intricate, and gain-medium inhomogeneity can have a pronounced impact on device performance.

While FP and DFB lasers emit light parallel to the wafer plane, vertical-cavity surface-emitting lasers (VCSELs) adopt a fundamentally different geometry. In VCSELs, the optical cavity is oriented perpendicular to the wafer surface and is formed by highly reflective distributed Bragg reflectors. This vertical configuration results in extremely short cavity lengths, strong longitudinal confinement, and small optical mode volumes [12]. VCSELs are distinguished by their low threshold currents, circular output beams, and suitability for wafer-level testing and high-

density integration. These advantages have made VCSELs the dominant light source for short-reach optical interconnects, particularly at wavelengths near 850 nm [13].

Extending VCSEL technology to longer wavelengths relevant to optical interconnects and telecommunication systems introduces additional challenges. At wavelengths around 1310 nm and 1550 nm, achieving high-reflectivity mirrors, sufficient optical confinement, and efficient carrier injection becomes more difficult, especially in InP-based material systems [14], [15]. The strong confinement inherent to VCSEL cavities places stringent requirements on the overlap between the optical mode and the gain medium, making device performance highly sensitive to active-region design. As a result, gain-medium properties that may be secondary considerations in FP or DFB lasers can become dominant limiting factors in VCSELs, particularly with respect to differential gain and modulation bandwidth.

Beyond these canonical architectures, a range of specialized semiconductor laser structures has been developed to address specific system requirements. External-cavity lasers, for example, offer ultra-narrow linewidth and wide tunability at the cost of increased complexity and size, making them suitable for high-performance coherent systems and sensing applications [16]. Photonic-crystal and surface-emitting lasers provide alternative approaches to mode control and beam shaping, though they are typically less mature for large-scale deployment in communication systems [17]. While such devices are not the primary focus of this dissertation, they underscore the diversity of design strategies employed to meet evolving optical communication demands.

Across all laser architectures, a recurring theme is the interplay between cavity design and gain-medium properties. FP lasers emphasize gain bandwidth and carrier dynamics over large volumes, DFB lasers demand spectral uniformity and precise mode control, and VCSELs impose extreme confinement and overlap requirements. These differences lead to distinct optimization priorities even when the same gain material is employed. Consequently, a gain medium that performs well in one laser architecture may not translate directly to another without careful redesign.

This diversity of laser structures highlights the importance of a device-level perspective when evaluating semiconductor gain materials. Rather than viewing gain media in isolation, their suitability must be assessed in the context of the intended cavity geometry and application scenario.

1.3 Gain Media for Semiconductor Lasers: From Quantum Wells to Quantum Dots and Quantum Dashes

The performance of a semiconductor laser is fundamentally determined by the properties of its gain medium, which governs carrier confinement, optical transition strength, and carrier–photon interaction dynamics. Over the past several decades, the development of laser gain media has followed a clear trend toward increased quantum confinement as a means of improving efficiency, temperature stability, and modulation performance. This evolution—from quantum wells to quantum dots and quantum dashes—reflects both advances in epitaxial growth techniques and the growing demands imposed by modern optical communication systems [18].

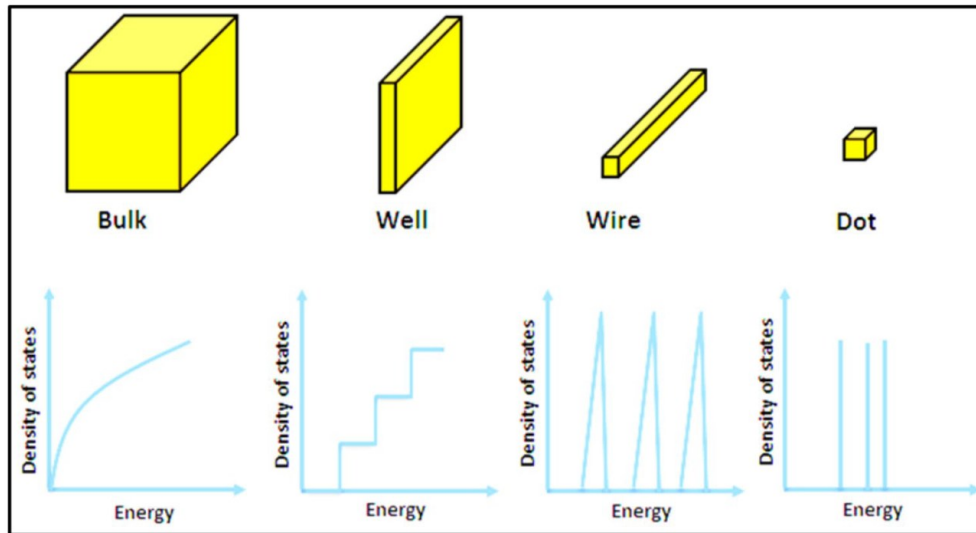


Figure 1.2 Density of states for bulk structure, quantum well, quantum wire and quantum dot [19]

Quantum well (QW) gain media have long served as the foundation of semiconductor laser technology. By confining carriers in one dimension, QWs enhance the overlap between electrons

and holes and increase the optical gain compared with bulk active regions. QW-based lasers have achieved exceptional maturity, offering high material gain, reliable fabrication, and excellent performance across a wide range of wavelengths and device architectures. As a result, QW lasers remain the dominant commercial solution in many optical communication applications. However, the quasi-two-dimensional density of states inherent to QWs leads to relatively strong temperature sensitivity and carrier leakage at elevated temperatures, particularly under high injection. These characteristics become increasingly limited as data rates rise and thermal margins shrink in densely integrated systems.

Quantum dot (QD) gain media represent a further step in confinement, with carriers localized in all three spatial dimensions. This strong confinement produces discrete energy states and a delta-function-like density of states in the ideal case, fundamentally altering carrier dynamics compared with QWs. As a result, QD lasers have demonstrated reduced temperature sensitivity [20], lower linewidth enhancement factors [21], and improved tolerance to optical feedback [22], [23]. These properties are particularly attractive for high-speed and low-noise optical communication systems. Nevertheless, practical QD ensembles inevitably exhibit size and composition variations, leading to inhomogeneous broadening of the optical transitions. While such broadening can be beneficial for broadband emission, it also complicates gain optimization and device uniformity [24].

In addition to their electronic advantages, QD gain media introduces new challenges related to gain magnitude and scalability. The small physical volume of individual dots limits the achievable material gain per active layer, making it difficult to reach lasing threshold without employing multiple stacked layers or high areal densities. Therefore, practical QD lasers often rely on multilayer active regions, which introduce additional considerations related to strain accumulation, carrier transport, and optical confinement [25], [26]. These factors become increasingly important as devices are pushed toward higher performance and tighter integration. Quantum dashes (Qdashes) can be viewed as an intermediate form between quantum wells and quantum dots, characterized by strong confinement in the growth direction and one lateral direction,

combined with extended dimensions along the orthogonal in-plane axis. In many material systems, particularly InAs/InP, anisotropic growth kinetics naturally lead to dash-like nanostructures with elongated shapes [27]. Qdashes are therefore especially well-suited for long-wavelength emission in the 1.3 μm and 1.55 μm bands, where achieving sufficient confinement and emission wavelength control can be challenging for conventional QDs.

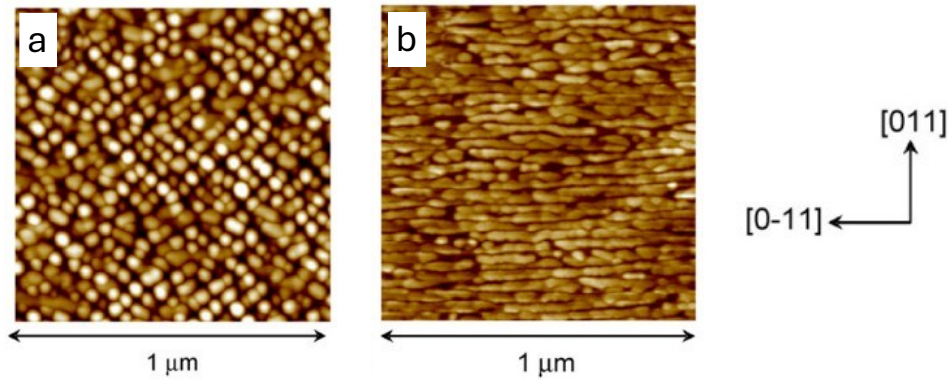


Figure 1.3 AFM images of InAs/InP : (a) Qdot, (b) Qdash [28]

From an electronic perspective, Qdashes retain many of the desirable features of QDs, including reduced temperature sensitivity and broadened gain spectra, while offering higher areal densities and stronger optical transition strength due to their extended geometry. These characteristics make Qdash gain media attractive for applications requiring broadband emission or high output power [24], [29]. However, the elongated morphology of Qdashes also leads to increased variability in lateral dimensions and spacing, further enhancing ensemble inhomogeneity. As with QDs, the limited vertical thickness of Qdashes constrains the achievable modal gain per layer, necessitating dense assemblies or multilayer stacking in practical devices.

Across QW, QD, and Qdash gain media, a recurring trade-off emerges between confinement-induced performance benefits and practical implementation challenges. While increased confinement improves temperature stability and noise performance, it simultaneously reduces the

active volume available for stimulated emission, placing greater emphasis on carrier capture efficiency, transport, and spatial distribution. In realistic devices, these competing effects must be carefully balanced through both material design and device architecture.

Importantly, as the media gain evolve toward lower-dimensional nanostructures, their behavior becomes increasingly sensitive to collective effects arising from dense assemblies and multilayer configurations. Although individual QDs or Qdashes can often be treated as isolated systems in simplified analyses, practical laser structures operate far from this idealized limit. Instead, interactions mediated by strain, carrier transport, and spatial proximity play an increasingly significant role in determining gain properties and device performance [30], [31].

In summary, the progression from quantum wells to quantum dots and quantum dashes reflects a broader shift toward gain media that offer enhanced intrinsic performance at the cost of increased structural and physical complexity. While QD and Qdash gain media provide compelling advantages for optical communication systems, their successful implementation requires a deeper understanding of how realistic ensembles behave within practical laser structures. This observation motivates the need for systematic investigation and predictive modeling approaches, which form the basis of the discussions in the following chapters.

1.4 Laser Requirements for Co-Packaged Optics Systems

The rapid scaling of data center bandwidth and the proliferation of artificial intelligence accelerators have driven a fundamental architectural transition in optical interconnect technology. As electrical input/output (I/O) bandwidth approaches the physical limits of copper interconnects, co-packaged optics (CPO) has emerged as a leading solution for next-generation high-density optical links [32]. Figure 1.4 shows the evolution of optical interconnect architectures from copper DAC and pluggable optics to on-board optics, 2.5D CPO, chiplet-based CPO, and 3D CPO. In CPO architecture, optical engines are integrated within the same package as high-performance switching or computing chips, significantly reducing electrical trace length and associated power

dissipation [8]. While this approach improves system-level energy efficiency and bandwidth density, it imposes stringent new requirements on semiconductor laser sources [33], [34], [35].

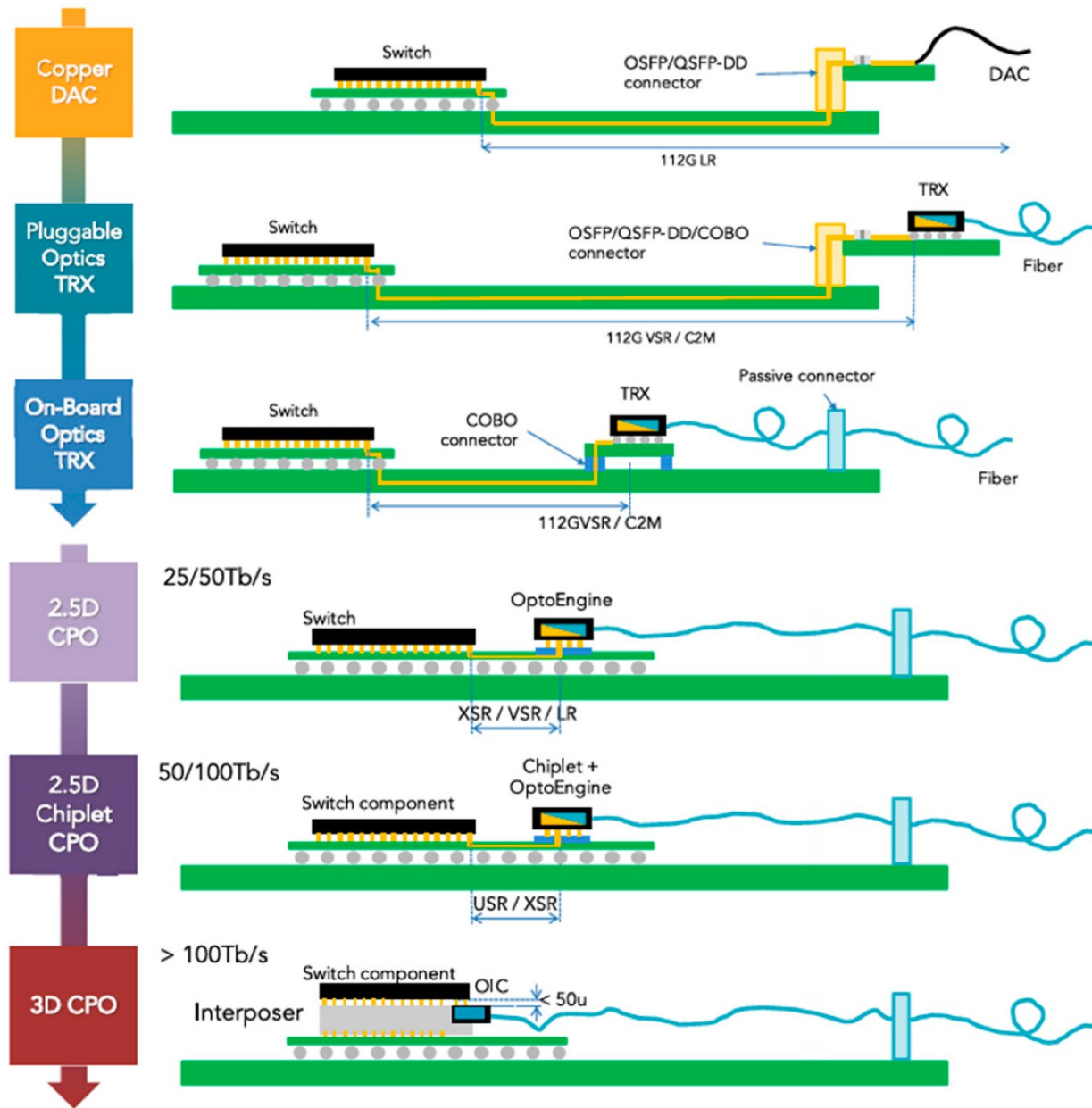


Figure 1.4 Evolution of optical interconnect architectures from copper DAC and pluggable optics to on-board optics, 2.5D CPO, chiplet-based CPO, and 3D CPO, illustrating progressively reduced electrical interconnect length and increasing system bandwidth beyond 100 Tb/s [32].

One of the most critical constraints in CPO systems is thermal robustness. Unlike traditional pluggable optical modules, which often employ thermoelectric coolers (TECs) to stabilize temperature, CPO platforms aim to eliminate active cooling to reduce power consumption and packaging complexity. As a result, laser devices may operate in ambient temperatures exceeding 80 °C and experience strong thermal gradients due to proximity to high-power electronic integrated circuits [34], [36]. Under such conditions, threshold current, differential gain, emission wavelength, and carrier leakage mechanisms become highly dependent on temperature. Therefore, lasers for CPO applications must exhibit low temperature sensitivity of threshold current and stable wavelength behavior without reliance on active temperature control.

In addition to thermal stability, tolerance to optical back reflection is a major requirement [37]. In tightly integrated photonic systems, reflections can originate from waveguide discontinuities, grating couplers, modulators, and imperfect facet terminations. The use of optical isolators within a co-packaged environment is often impractical due to space and cost constraints. Consequently, reflected light may re-enter the laser cavity and interact with the intracavity field. Such feedback can induce excess relative intensity noise (RIN), linewidth broadening, mode hopping, and, in severe cases, coherence collapse. Designing laser cavities and gain media that exhibit inherent reflection tolerance—through optimized differential gain, reduced linewidth enhancement factor, and controlled photon lifetime—is therefore essential for reliable CPO operation [38].

Low noise characteristics are equally important. In high-speed intensity-modulated direct-detection (IMDD) links, excess RIN directly degrades signal-to-noise ratio and limits achievable link distance [39]. For emerging coherent or advanced modulation formats, phase noise and linewidth become even more critical performance metrics. The linewidth enhancement factor (α -factor), which quantifies the coupling between amplitude and phase fluctuations, strongly influences chirp and feedback sensitivity. Gain media with reduced α -factor and stable carrier dynamics are therefore preferred in CPO systems to maintain signal integrity under high-speed modulation [40], [41].

Energy efficiency represents another fundamental design constraint [42]. Since hundreds of optical channels may be integrated within a single co-packaged module, small improvements in threshold current or modulation efficiency translate into substantial reductions in overall system power consumption. High differential gain enables increased modulation bandwidth at lower bias current, while efficient carrier confinement reduces carrier leakage and non-radiative recombination losses. Thus, engineering the gain medium to enhance carrier–photon coupling efficiency is directly linked to lowering energy per transmitted bit [43], [44].

Finally, integration compatibility must be considered. Lasers used in CPO must be compatible with heterogeneous integration platforms, including silicon photonics and wafer-fusion techniques. This requires careful management of strain, thermal expansion mismatch, and epitaxial layer design to ensure reliability under thermal cycling and high current density operation.

Qdot and Qdash gain media provide several intrinsic advantages aligned with these requirements. Carrier localization in discrete states reduces temperature sensitivity and suppresses leakage. The typically smaller linewidth enhancement factor improves chirp and feedback tolerance. Furthermore, the ability to engineer strain distribution, confinement layers, and coupling effects offers additional degrees of freedom for optimizing differential gain and dynamic response. However, intrinsic advantages alone are insufficient; deliberate bandgap, strain, and coupling engineering are required to meet the increasingly stringent demands of CPO systems [33], [45], [46].

1.5 State of the Art in Qdot and Qdash Lasers

1.5.1 Qdot/dash Mode-Lock Lasers

Broadband and multi-wavelength semiconductor light sources are foundational components for wavelength-division multiplexing (WDM) transmitters, chip-scale optical frequency combs, and low-coherence sources used in sensing and imaging. In optical interconnects and telecom systems, multi-wavelength sources reduce the footprint and power of transmitter assemblies by

replacing arrays of distributed-feedback lasers with a single device that provides many stable carriers. In photonic integrated circuits, a monolithic comb source further simplifies wavelength generation and distribution, enabling dense WDM and coherent carrier generation with reduced packaging complexity. Figure 1.5 shows the schematic illustration of dense wavelength division multiplexing (DWDM) for bidirectional optical communication [47]. Qdot/dash gain media are particularly attractive in this context because their discrete energy states and natural inhomogeneous broadening support wide gain spectra without requiring strong nonlinear processes, and because their low linewidth enhancement factor can improve feedback tolerance and comb stability in integrated environments [48], [49], [50]. Reviews focused on Qdot/dash lasers for photonic integration provide a useful overview of why Qdot/dash sources are increasingly viewed as practical multi-wavelength engines for integrated photonics.

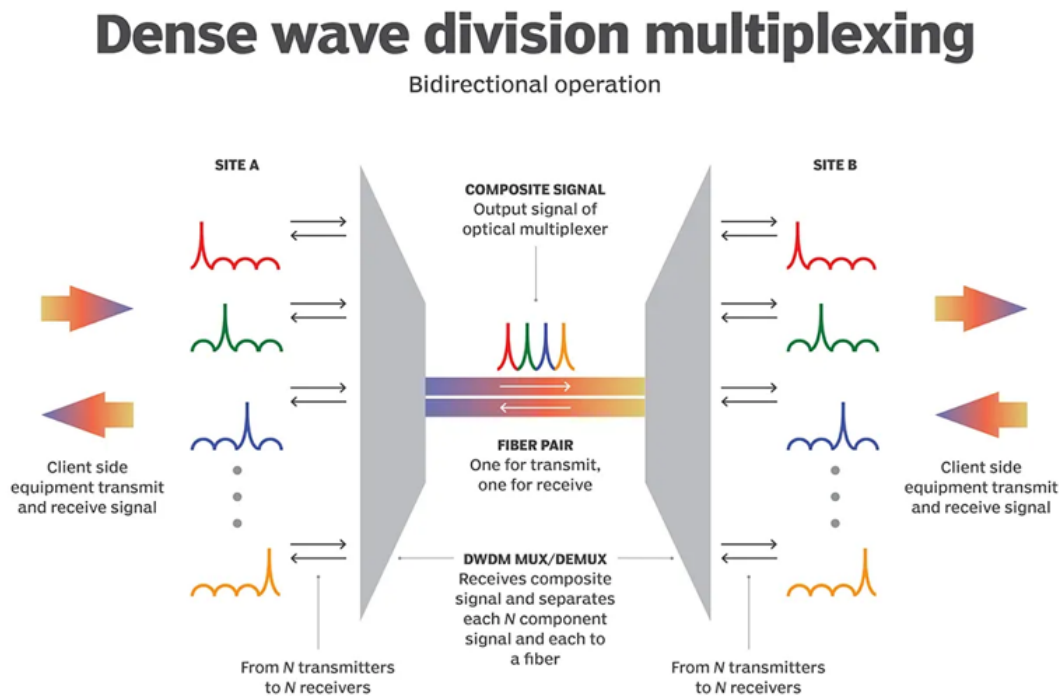


Figure 1.5 Schematic illustration of dense wavelength division multiplexing (DWDM) for bidirectional optical communication, where multiple wavelength channels are multiplexed onto a single fiber and separated at the receiver using optical MUX/DEMUX devices [47].

The dominant research trend for broadband Qdot/dash emitters can be summarized as “engineer the ensemble,” i.e., deliberately shaping the distribution of optical transition energies across nanostructures while maintaining sufficient carrier capture and confinement. In practice, this has led to several complementary techniques. The first is to intentionally increase inhomogeneous broadening through growth-condition control, producing wider dot-size distributions and hence wider spontaneous and gain spectra [51], [52]. A second, more controlled approach is chirped stacking, where multiple layers are grown with systematically varied nanostructure dimensions so that each layer contributes a slightly different transition energy [53], [54]. Chirped multilayer designs have been widely used in broadband superluminescent diodes (SLEDs), where the goal is to maximize spectral width while suppressing lasing; the broader Qdot/dash ensemble directly translates into larger emission bandwidth [55], [56].

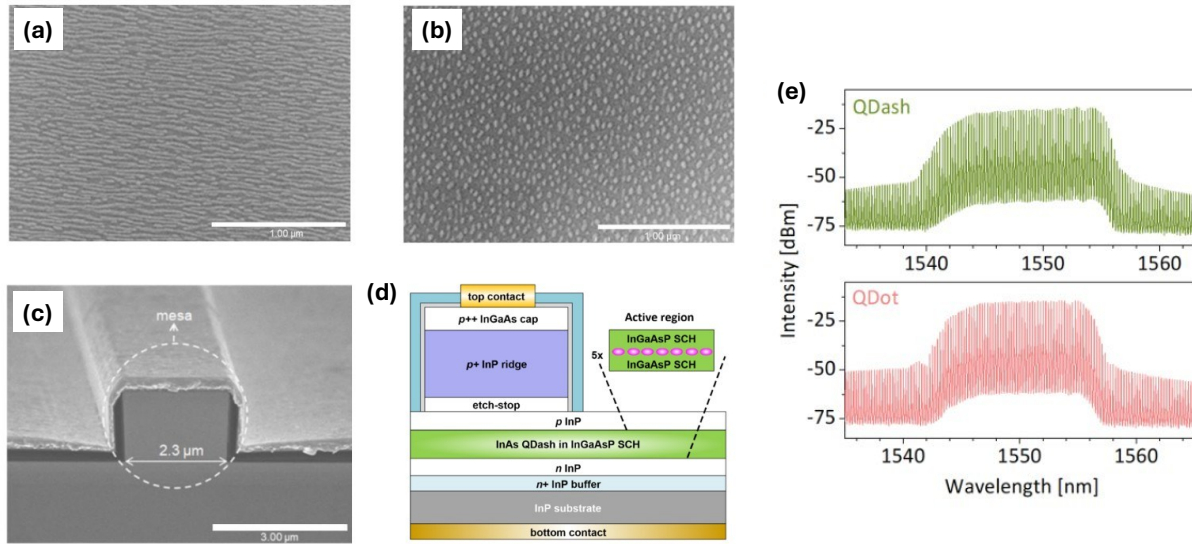


Figure 1.6 Structural and optical characteristics of QDash and QDot laser devices. (a) SEM image of self-assembled quantum dashes. (b) SEM image of self-assembled quantum dots. (c) Cross-sectional SEM image of the fabricated ridge waveguide with a width of 2.3 μm. (d) Schematic layer structure of the QDash laser. (e) Measured optical frequency comb [57].

A closely related line of work is the development of Qdot/dash sources specifically for optical frequency comb generation, most commonly using passively or self-mode-locked Fabry–Pérot ridge lasers [58]. These devices provide comb lines spaced by the cavity free spectral range, often tens of GHz, and can be directly current-driven, making them attractive compared with Kerr microcombs that require a low-noise pump laser and precise thermal control. InAs/InP Qdash mode-locked lasers have been repeatedly demonstrated as compact comb generators with favorable stability and noise characteristics, and they have been applied to coherent WDM transmission experiments as a scalable carrier source [59]. Beyond communications, Qdash mode-locked combs have also been used in metrology-style applications such as dual-comb ranging, reflecting a broader trend toward semiconductor comb sources as enabling technology for compact sensing systems [60], [61]. More general reviews on semiconductor mode-locked lasers and on-chip comb sources are also helpful for situating QD/Qdash combs within the larger comb ecosystem.

From a technical standpoint, three device-level directions dominate current Qdot/dash broadband and multi-wavelength research. The first is spectral flatness and gain equalization, since WDM and comb applications require not only wide spectra but also relatively uniform line powers. Approaches include optimizing the number of stacks and their chirp profile, tailoring carrier capture into different sub-ensembles, and engineering the optical cavity (facet reflectivity, dispersion, intracavity filtering) to reduce mode competition [26], [62], [63], [64], [65]. The second direction is noise and stability control, including suppression of timing jitter and phase noise, which directly impacts coherent transmission quality [66], [67], [68], [69]. Studies on frequency and timing stability of Qdash combs illustrate how device design and operating conditions affect comb coherence and long-term stability. The third direction is PIC compatibility, where emphasis shifts to integrating comb sources with on-chip reflectors, filters, and modulators while maintaining stable mode-locking. Early demonstrations of single-section Qdash comb sources

explicitly targeted photonic integrated circuit operation, underscoring the continuing trend toward monolithic multi-wavelength transmit engines [70], [71].

1.5.2 Low-Threshold and High Thermal Stability Qdot/dash Lasers

Low threshold current and improved temperature stability are among the most frequently cited advantages of Qdot/dash semiconductor lasers [72], [73]. From a system perspective, low threshold directly reduces power consumption and improves wall-plug efficiency, which is particularly critical in high-density optical interconnects and co-packaged optics systems. Temperature stability, often quantified by the characteristic temperature T_0 , determines how strongly threshold current increases with ambient temperature. Devices operating without active cooling must maintain stable performance across wide thermal variations, making these metrics central to practical deployment.

The theoretical foundation for low-threshold QD lasers can be traced to the pioneering work of Arakawa and Sakaki [74], [75], who proposed that three-dimensional carrier confinement reduces threshold current by suppressing thermally activated carrier escape into higher-dimensional states. The discrete density of states limits the number of available carrier states near the band edge, thereby reducing the transparency carrier density. Experimental demonstrations in InAs/GaAs QD lasers soon confirmed reduced threshold current density compared with quantum-well devices, in some cases achieving threshold densities below 100 A/cm² and improved temperature stability.

For long-wavelength operation in the InAs/InP material system, Qdash lasers have attracted significant attention due to their compatibility with telecom bands. InAs/InGaAsP Qdash lasers have demonstrated relatively high characteristic temperatures and moderate threshold currents at 1.55 μm . Compared with QW counterparts, Qdash lasers often exhibit reduced carrier leakage at elevated temperatures, attributed to stronger carrier localization and deeper effective confinement in discrete states [76], [77]. Additionally, the typically smaller linewidth enhancement factor in Qdot/dash lasers can improve dynamic stability under back reflection [78], [79].

However, despite these intrinsic advantages, achieving simultaneously low threshold and high-temperature stability in practical devices remains challenging. Several competing mechanisms limit performance. First, while carrier localization suppresses leakage, it can also reduce carrier redistribution efficiency across inhomogeneous ensembles. In realistic Qdot/dash structures, size dispersion leads to a distribution of transition energies, and carriers may become trapped in higher-energy nanostructures instead of efficiently relaxing into the lowest-energy states that dominate lasing. Second, Auger recombination and defect-assisted non-radiative recombination become increasingly significant at high carrier density and elevated temperature, particularly in long-wavelength systems where the bandgap is smaller.

1.5.3 Qdot/dash VCSELs

Vertical-cavity surface-emitting lasers (VCSELs) have become indispensable light sources for short-reach optical interconnects due to their low power consumption, circular beam profile, wafer-level testability, and compatibility with high-density array fabrication. For datacenter and high-performance computing applications, modulation bandwidth and energy efficiency are the primary performance metrics. While short-wavelength (850–980 nm) GaAs-based VCSELs have achieved modulation bandwidths exceeding 25–30 GHz through aggressive cavity shortening and parasitic reduction [80], [81], extending comparable performance to long-wavelength (1.3–1.55 μm) devices remains a significant challenge [82], [83].

Qdot/dash gain media have been explored as candidates for high-speed VCSEL operation because of their potentially higher differential gain and reduced linewidth enhancement factor compared with quantum wells. The discrete density of states in Qdot/dash systems can lead to steeper gain–carrier dependence near threshold, increasing the relaxation-oscillation frequency and thereby enhancing modulation bandwidth. Additionally, reduced α -factor improves chirp characteristics and dynamic stability under high-speed operation.

In GaAs-based short-wavelength systems, Qdot/dash VCSELs have demonstrated promising dynamic performance, including bandwidths exceeding 20 GHz under optimized cavity conditions.

However, long-wavelength Qdot/dash VCSELs introduce additional complexity. First, InP-based active regions must be integrated with high-reflectivity distributed Bragg reflectors (DBRs), often via wafer-fusion techniques [84], [85], [86]. This hybrid approach increases effective cavity length and photon lifetime, which inherently limits modulation bandwidth. Second, the smaller bandgap of long-wavelength materials enhances Auger recombination and non-radiative processes, which degrade differential gain and increase damping. Third, achieving precise emission wavelength control in the C-band while maintaining strong carrier confinement is more difficult in InAs/InP Qdot/dash systems due to the strong red shift associated with increasing nanostructure height.

As a result, many reported improvements in long-wavelength VCSEL performance have focused primarily on cavity engineering rather than gain-medium optimization. Techniques such as reducing oxide aperture diameter, optimizing distributed Bragg reflector pairs, and minimizing parasitic capacitance and resistance have been widely employed to enhance bandwidth [87], [88], [89]. While these approaches effectively increase the relaxation-oscillation frequency by reducing photon lifetime or parasitic limitations, they do not fundamentally modify the intrinsic gain dynamics of the active region.

1.6 Overview of modeling Qdot/dash laser

Simulation of Qdot and Qdash lasers has evolved substantially over the past two decades as modeling approaches have shifted toward capturing the nanoscale physics of strongly confined carriers. Early work on InAs/GaAs QDs by Arakawa and Sakaki established the foundational concepts of three-dimensional carrier confinement, demonstrating enhanced differential gain and reduced temperature sensitivity[90]. These ideas motivated the development of multi-reservoir rate-equation models that include separate wetting layer (WL), excited state (ES), and ground state (GS) populations, as pioneered by research groups such as Bimberg and Blood [18], [91], [92]. These models remain widely used due to their ability to reproduce threshold behavior, gain saturation, and modulation responses while maintaining computational simplicity.

As material systems shifted from QDot to elongated Qdash—particularly InAs/InP for C-band and L-band telecommunication lasers—more sophisticated electronic-structure simulations became necessary. 8-band $k \cdot p$ methods, including strain and piezoelectric effects, became the standard for computing the energy levels and optical matrix elements of realistic dash geometries [93], [94].

On the device level, optical cavity modeling using finite-difference time-domain (FDTD) and finite-element method (FEM) tools (e.g., COMSOL, Lumerical) has become essential for calculating the optical confinement factor, spatial hole burning, and Q-factor in edge-emitting structures and VCSELs [95], [96].

In parallel, time-domain simulations of dynamic behavior—such as modulation response, polarization switching, and spin-photon interactions. These approaches capture ultrafast processes including carrier relaxation, capture/escape dynamics, and gain compression, which are critical for predicting high-speed operation [97], [98], [99].

1.7 Summary

This chapter has provided a broad overview of the technological context in which modern semiconductor lasers operate. The rapid development of optical interconnects and telecommunication systems has imposed increasingly stringent requirements on laser sources, including high modulation bandwidth, low noise, thermal stability, and energy-efficient operation at standardized wavelength bands. To meet these diverse system-level demands, a variety of semiconductor laser architectures—such as Fabry–Perot lasers, distributed feedback lasers, and vertical-cavity surface-emitting lasers—have been developed, each optimized for specific application scenarios and operating constraints.

The evolution of laser gain media from quantum wells to quantum dots and quantum dashes reflects a parallel effort to improve intrinsic material performance through enhanced carrier confinement. While quantum-dot and quantum-dash gain media offer notable advantages in terms

of temperature stability, noise performance, and gain bandwidth, their practical implementation introduces new challenges associated with reduced modal gain per layer and increased structural complexity. As a result, realistic devices rely on dense and multilayer gain-media assemblies whose collective behavior cannot be fully understood by considering individual nanostructures in isolation.

Taken together, these considerations highlight a growing gap between the intrinsic advantages offered by advanced gain materials and the ability to predict and optimize their performance within practical laser devices across different architectures. Addressing this gap requires a clear formulation of the underlying challenges and a systematic approach to modeling that links material properties to device-level behavior.

Chapter 2 Problem Statement and Research Motivation

2.1 From Background to the Fundamental Design Challenge

The preceding chapter outlined the rapid evolution of optical interconnect and telecommunication systems, the diversity of semiconductor laser architectures employed in these systems, and the progression of laser gain media toward increasingly confined nanostructures. Together, these developments highlight a central tension in modern laser design: while advanced gain materials are required to meet stringent system-level requirements, their intrinsic physical properties introduce new challenges that complicate predictive device engineering.

Quantum-dot and quantum-dash gain media have attracted sustained interest because their strong carrier confinement offers advantages over conventional quantum-well active regions, including improved temperature stability, reduced linewidth enhancement factor, and broadened gain spectra. These properties are particularly attractive for high-speed and energy-efficient optical communication systems. However, the same confinement mechanisms that enable these benefits also impose a fundamental limitation on the achievable modal gain. Unlike quantum wells, where the active region extends continuously across the device plane, QD/Qdash gain media consist of spatially localized nanostructures embedded in a wider-bandgap matrix. As a result, only a small fraction of the optical mode volume directly overlaps with optically active material.

At the level of individual nanostructures, optical transitions in QDs and Qdashes can be strong, and their discrete density of states enhances certain aspects of carrier–photon interaction. Nevertheless, laser operation depends on the collective contribution of a large ensemble of nanostructures interacting with a cavity mode. In practical material systems, the areal density of QDs or Qdashes within a single layer is constrained by epitaxial growth considerations such as strain accumulation, defect formation, and morphological stability [100], [101]. Consequently, the net material gain provided by a single QD/Qdash layer is typically insufficient to satisfy the lasing

threshold condition, particularly in long-wavelength devices where optical confinement is inherently weaker.

The limited vertical thickness of QD/Qdash active regions further exacerbates this challenge. In many InAs/InP-based systems, the height of individual nanostructures is only a few nanometers, leading to a very small effective gain thickness compared with quantum-well-based active regions. While quantum wells can be readily stacked to increase gain without fundamentally altering their electronic structure, QD/Qdash systems cannot rely on a single active layer to achieve comparable modal gain. As a result, simply adopting QD/Qdash gain media within established laser architectures does not automatically translate into viable devices without additional design strategies.

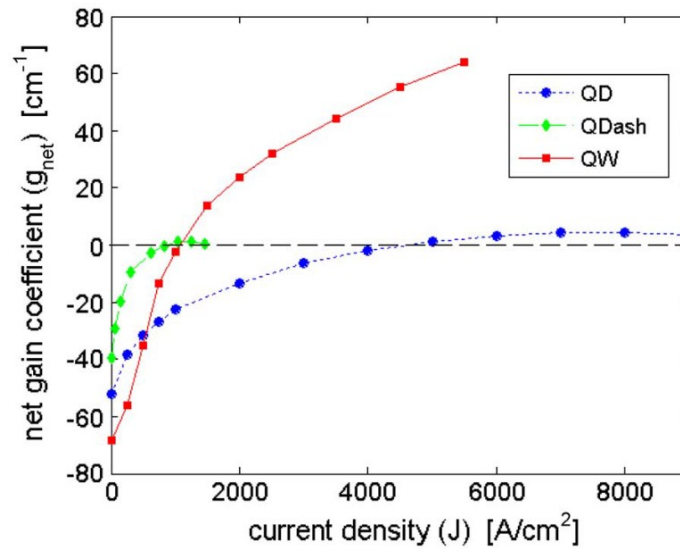


Figure 2.1 Net gain coefficient g versus applied current density, for the SOAs of three different gain mediums [77].

To overcome this intrinsic gain limitation, practical QD/Qdash lasers inevitably employ dense ensembles of nanostructures, achieved through increased areal density within a layer, multilayer stacking along the growth direction, or a combination of both. Multilayer active regions have therefore become a standard feature of QD/Qdash lasers, particularly for applications targeting the

O- and C-band wavelength ranges [102], [103]. This design choice is not an optimization aimed at incremental performance improvement, but rather a fundamental requirement for enabling lasing in the first place.

Importantly, the necessity of dense and multilayer QD/Qdash assemblies fundamentally distinguishes these gain media from their quantum-well counterparts. By increasing the density and spatial proximity of nanostructures, the gain medium transitions from a collection of nominally isolated emitters to a complex, interacting ensemble. In this regime, the electronic and optical properties of the gain medium are no longer determined solely by individual nanostructures, but by collective effects that emerge from their arrangement, interaction, and coupling [104].

This observation defines the central design challenge addressed in this dissertation. The advantages of QD/Qdash gain media can only be realized in practical devices by operating in regimes where dense assemblies are unavoidable, yet these same regimes introduce physical interactions that are difficult to predict and control using conventional modeling approaches. Understanding and managing this interplay between intrinsic material limitations and necessary structural complexity is therefore a prerequisite for the predictive design of QD/Qdash lasers, and it motivates the discussion of dense-assembly-induced coupling effects in the following section.

2.2 Dense QD/Qdash Assemblies and Unavoidable Coupling Effects

The requirement for dense and multilayer QD/Qdash gain media, established in the previous section, has profound physical consequences that extend beyond simple scaling of optical gain. As spatial separation between nanostructures is reduced to achieve sufficient modal gain, interactions between neighboring structures become increasingly significant. These interactions, collectively referred to as coupling effects, are not incidental features of specific designs but intrinsic outcomes of operating QD/Qdash gain media in realistic device regimes.

In multilayer active regions, coupling emerges first along the growth direction through the accumulation and propagation of strain fields [101]. Each buried layer of QDs or Qdashes

introduces strain into the surrounding matrix, and as additional layers are stacked, these strain fields interact and overlap. The resulting modification of the local band structure influences the confinement potential, transition energies, and carrier localization of subsequently grown layers. Importantly, such strain-mediated interactions do not require direct electronic wavefunction overlap between layers; even when spacer layers are sufficiently thick to suppress strong tunneling, vertical coupling can persist through elastic interactions alone. As stacking depth increases, these effects accumulate, leading to systematic variations in the electronic properties of the gain medium that cannot be captured by treating each layer independently.

In addition to vertical interactions, dense QD/Qdash assemblies give rise to lateral coupling within the plane of the active region [105]. This effect is particularly relevant for Qdash systems, where elongated in-plane morphology and high areal density naturally reduce the spacing between neighboring structures. Under these conditions, carriers, especially electrons with relatively small effective masses, can redistribute laterally through tunneling-assisted or thermally activated processes. Even when such transport is weak on the scale of individual nanostructures, its cumulative influence across a dense ensemble can significantly modify carrier occupation and recombination dynamics at the gain-medium level.

Crucially, coupling effects do not rely on idealized conditions such as perfect alignment, identical nanostructures, or resonant energy levels. In realistic QD/Qdash ensembles, variations in size, shape, and composition introduce inhomogeneity that broadens the distribution of confined states. Coupling mechanisms operate within this inhomogeneous landscape, often enhancing redistribution and interaction rather than suppressing it [106]. As a result, coupling should be regarded as a robust feature of dense assemblies, rather than a fragile effect that appears only under narrowly defined conditions.

The impact of coupling extends beyond material properties to influence how gain media interact with different laser architectures. While the specific manifestation of coupling effects depends on optical confinement and cavity geometry, their physical origin resides in the gain medium itself.

In larger-volume devices, such as Fabry–Perot lasers, coupling-induced modifications of the gain spectrum and carrier distribution can directly influence spectral and threshold behavior. In strongly confined devices, such as VCSELs, the same coupling mechanisms interact with cavity eigenmodes and mode volume constraints, potentially amplifying or suppressing their effects [107]. In all cases, coupling cannot be cleanly separated from device considerations once dense assemblies are employed.

Despite its intrinsic nature, coupling in QD/Qdash gain media is frequently treated implicitly or neglected altogether in simplified design approaches. Effective gain parameters, isolated-layer approximations, or phenomenological fitting can obscure the role of coupling and limit the ability to predict how changes in material design or structural configuration will influence device performance. As device requirements become more stringent and design margins narrower, such simplifications become increasingly inadequate.

Recognizing coupling as an unavoidable consequence of dense QD/Qdash assemblies therefore represents a critical conceptual shift. Rather than being viewed as a parasitic effect to be minimized or averaged out, coupling must be treated as a fundamental aspect of gain-medium behavior that can either constrain or enable device performance, depending on how it is managed. This realization places new demands on modeling approaches, which must be capable of capturing coupling effects in a physically consistent and device-relevant manner. The limitations of existing modeling strategies in this regard are examined in the following section.

2.3 Limitations of Existing Modeling Approaches

The emergence of dense assemblies and unavoidable coupling effects in QD/Qdash gain media places stringent demands on modeling approaches intended for laser design. To be predictive, such approaches must simultaneously account for nanoscale electronic structure, collective interactions within realistic ensembles, and device-specific optical confinement. While substantial progress has been made in modeling semiconductor lasers, existing approaches

typically address only subsets of these requirements, limiting their applicability to dense and strongly coupled gain media.

Material-level electronic-structure models have played a central role in advancing the understanding of QD/Qdash systems. Methods based on multi-band $k \cdot p$ theory, effective-mass approximations, and atomistic techniques can accurately capture confinement, strain effects, and optical transition properties of individual nanostructures or small representative systems [108], [109]. These models are indispensable for revealing how geometry, composition, and strain influence electronic states. However, they are inherently limited in scope. By focusing on isolated nanostructures or simplified stacks, they do not naturally capture the collective behavior of dense ensembles or their interaction with an optical cavity. As a result, the connection between calculated electronic states and the macroscopic gain experienced by a laser mode remains indirect, particularly when coupling effects play a significant role.

At the opposite end of the modeling spectrum, device-level laser models are designed to describe carrier–photon dynamics within an optical cavity. Rate-equation and traveling-wave formulations have been widely used to analyze threshold behavior, modulation response, and noise characteristics across many laser technologies [97], [99]. These models are computationally efficient and well suited for system-level exploration once key parameters are known. However, they typically rely on simplified or empirical descriptions of the gain medium, often assuming uniform carrier distributions and parameterized gain functions. While such assumptions are reasonable for mature technologies with well-characterized materials, they obscure the influence of nanostructure geometry, ensemble inhomogeneity, and coupling effects that are intrinsic to QD/Qdash gain media.

Recognizing the complementary strengths of material-level and device-level approaches, several studies have attempted to bridge the two by extracting gain-related parameters from electronic-structure calculations and incorporating them into laser-dynamics models [110]. These partial integration strategies represent an important step toward more physically grounded

simulations. Nevertheless, the integration is often incomplete. In many cases, information flows only in one direction—from material calculations to device models—without feedback from cavity properties or carrier dynamics back into the electronic structure. Optical cavity effects are frequently treated using simplified confinement factors rather than explicit eigenmode analysis and coupling effects arising from dense assemblies are commonly absorbed into effective parameters or neglected altogether.

These limitations become particularly pronounced when modeling devices with strong optical confinement or when exploring new gain-medium designs outside experimentally calibrated regimes. In such cases, simplified overlap assumptions and empirical gain models provide limited guidance for predicting how changes in growth parameters, stacking configurations, or device geometry will influence performance. This disconnect is especially problematic for VCSELs, where cavity eigenmodes and spatial field distributions strongly shape gain–mode interaction, and for densely stacked QD/Qdash systems, where coupling effects modify electronic states and carrier distributions in a nontrivial manner.

Taken together, existing modeling approaches offer either physical accuracy without device context or device-level insight without detailed material fidelity. Partial integration strategies narrow this gap only partially and often lack the ability to treat coupling effects and cavity-specific interactions in a unified and self-consistent manner. Consequently, they provide limited predictive capability for QD/Qdash lasers operating in dense, strongly interacting regimes.

These observations underscore the need for a modeling approach that does not treat electronic structure, coupling phenomena, and optical confinement as separable problems. Instead, a tightly integrated device-level simulation framework is required—one that can consistently link nanoscale material physics to macroscopic laser behavior across different architectures. The formulation of such a framework, along with its guiding objectives and scope, is described in the following section.

2.4 Research Motivation and Objectives

2.4.1 Research Motivation

Qdot/dash gain media offer intrinsic advantages over conventional QW structures, including improved temperature stability, reduced noise, and broadened gain spectra. However, these benefits come with a fundamental limitation: the small physical volume of quantum-confined nanostructures restricts the achievable modal gain of a single active layer. As a result, practical QDot/dash lasers necessarily rely on dense in-plane assemblies and multilayer stacking to reach lasing threshold.

Operating in this dense-assembly regime fundamentally alters the behavior of the gain medium. Vertical strain accumulation, interlayer electronic coupling, and lateral carrier tunneling emerge naturally as nanostructures are brought into proximity. These coupling effects reshape electronic states, carrier redistribution, and optical transition strengths, and therefore play a decisive role in determining device performance. Importantly, such interactions are not optional design features, but unavoidable consequences of the structures required for practical laser operation.

Despite this, many existing modeling approaches treat Qdot/dash as effectively isolated emitters, relying on empirical gain parameters or simplified rate-equation descriptions. While such approximations can reproduce specific experimental results, they obscure the physical origin of performance limitations and offer limited predictive capability when exploring new material designs, stacking strategies, or laser architectures. This limitation becomes particularly severe in devices with strong optical confinement, such as VCSELs, where small changes in gain-medium properties can have a disproportionately large impact on laser dynamics.

The motivation of this work is therefore to develop a modeling approach that explicitly links nanoscale material physics to device-level laser behavior. By capturing coupling effects, strain–band structure interactions, and cavity–gain interplay within a unified framework, this research aims to provide a physically grounded basis for the predictive design of Qdot/dash lasers.

2.4.1 Research Objectives

The primary objective of this dissertation is to develop and apply a unified, physics-based simulation framework for semiconductor lasers employing Qdot/dash gain media. The framework integrates electronic-structure modeling, optical cavity eigenmode analysis, and time-domain laser dynamics to enable consistent, multiscale device-level prediction.

The specific objectives are to:

1. Develop a unified multi-physics simulation platform that couples eight-band $k \cdot p$ electronic-structure calculations, full-vector cavity eigenmode analysis, and time-domain traveling-wave laser modeling.
2. Investigate vertical coupling effects in multilayer Qdot/dash active regions, including strain accumulation, interlayer electronic coupling, and stacking sequence, and determine how these effects influence gain spectra and broadband laser performance.
3. Analyze lateral coupling and carrier transport in dense Qdash ensembles, with emphasis on tunneling-mediated carrier redistribution and its impact on threshold behavior and gain efficiency.
4. Apply the unified framework to different laser architectures, including Fabry–Perot lasers and VCSELs, to elucidate how gain-medium physics interacts with weak and strong optical confinement.
5. Demonstrate the framework through representative device studies, including broadband mode-locked lasers, low-threshold Qdash lasers, and high-speed C-band VCSELs.

Through these objectives, this work seeks to provide both physical insight and practical modeling tools for the design and optimization of advanced quantum-confined semiconductor lasers for optical interconnect and integrated photonics applications.

Chapter 3 Background Theory and Calculation Methods

3.1 Framework Overview and Design Philosophy

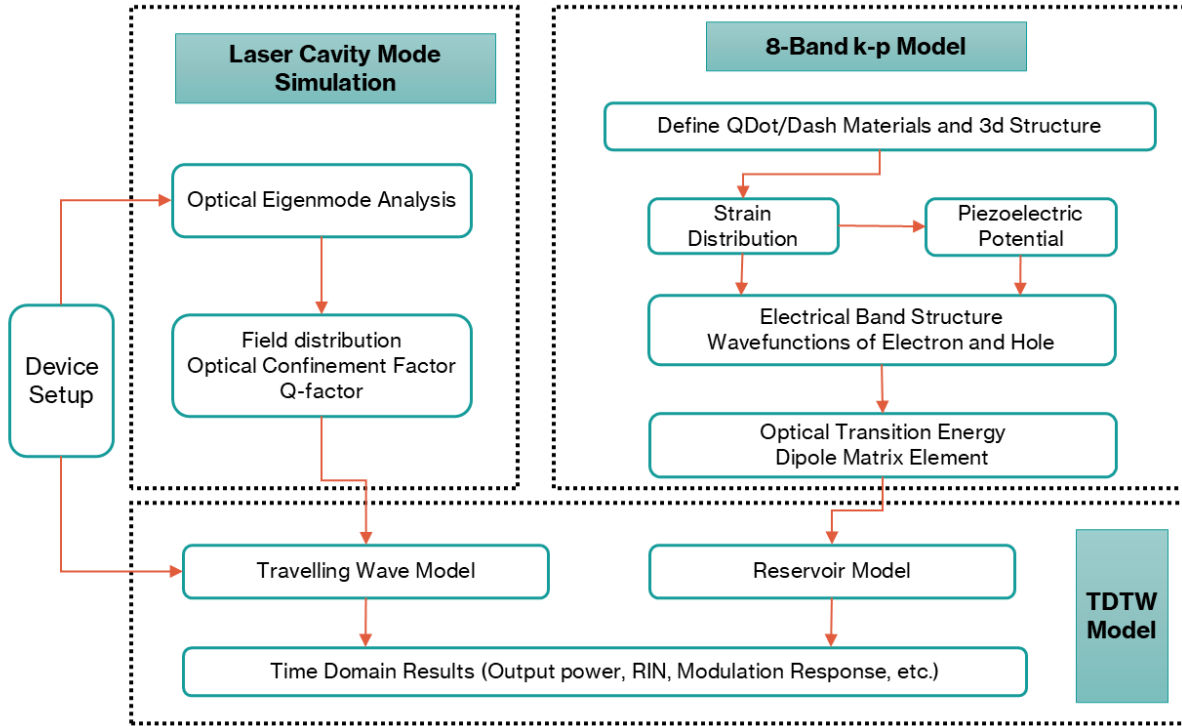


Figure 3.1 Schematic diagram of the unified simulation framework.

The integrated simulation framework developed in this work is designed to provide a physically consistent link between electronic structure, optical cavity properties, and time-domain laser dynamics in QD/Qdash devices. As illustrated in Figure 3.1, the framework is organized into three primary modeling layers: (i) optical cavity mode simulation, (ii) electronic structure modeling based on an 8-band $k \cdot p$ formalism, and (iii) device-level carrier-photon dynamics implemented through a travelling-wave time-domain (TDTW) model. These layers are connected through well-defined physical interfaces that allow material-level modifications to propagate naturally to device-level performance metrics.

At the device-geometry level, the simulation begins with the specification of the laser structure, including layer stack, cavity dimensions, and material parameters. This device setup serves as the

common input to both the optical and electronic modeling branches. On the optical side, cavity eigenmode analysis is performed to determine the spatial field distribution, optical confinement factor, and cavity quality factor. Unlike simplified approaches that approximate optical confinement using constant overlap factors, this framework explicitly computes eigenmodes, ensuring that gain–mode interaction is evaluated based on realistic spatial distributions. This treatment is particularly important for strongly confined devices such as VCSELs, where small variations in active-region placement or thickness can significantly alter mode overlap and device behavior.

In parallel, the electronic structure of the QD/Qdash gain medium is modeled using an 8-band $k \cdot p$ approach. Realistic three-dimensional nanostructure geometry and material composition are first defined, followed by calculation of strain distribution and piezoelectric potential within the active region. These fields are then incorporated into the multi-band Hamiltonian to obtain the electronic band structure and confined wavefunctions for electrons and holes. From these wavefunctions, optical transition energies and dipole matrix elements are extracted. This sequence ensures that confinement, strain effects, and band mixing are treated consistently, providing a physically grounded description of the gain medium.

The outputs of the optical and electronic modules are then combined at the device-dynamics level. Transition energies and dipole matrix elements obtained from the 8-band $k \cdot p$ model are used to construct gain-related parameters within a reservoir model that accounts for carrier occupation and redistribution. Simultaneously, optical confinement factors and field distributions derived from eigenmode analysis determine the effective interaction between the gain medium and the cavity mode. These quantities are supplied to a travelling-wave model that solves the coupled carrier–photon equations in the time domain.

The travelling-wave time-domain (TDTW) module forms the final layer of the framework, producing time-resolved device observables such as output power, relative intensity noise (RIN), and modulation response. By integrating material-derived transition properties and explicitly

calculated cavity parameters, the TDTW model avoids reliance on purely empirical gain functions. Instead, device performance emerges from the combined influence of electronic structure, coupling-induced modifications, and cavity geometry.

A central design philosophy of this framework is modular integration with physically meaningful data exchange. Each modeling block operates at an appropriate level of fidelity: the 8-band $k \cdot p$ model captures nanoscale electronic physics; eigenmode analysis resolves optical confinement; and the TDTW model describes macroscopic laser dynamics. Rather than collapsing these layers into a single monolithic simulation or linking them through loosely fitted parameters, the framework preserves explicit physical connections between modules. This approach enables systematic exploration of how changes in nanostructure design, stacking configuration, or cavity geometry influence device-level performance across different laser architectures.

Importantly, the framework is architecture-agnostic at the material level. The same electronic structure description can be coupled to different cavity geometries by recalculating the corresponding eigenmodes and confinement factors. This flexibility allows consistent comparison between Fabry–Perot lasers and VCSELs within a unified modeling environment, a capability that is essential for investigating platform-dependent manifestations of coupling effects.

3.2 Laser cavity eigenmode analysis

Accurate modeling of laser behavior requires explicit determination of the spatial and temporal characteristics of the optical modes supported by the cavity. Rather than approximating optical confinement through fixed overlap factors or assumed field profiles, the present framework derives these quantities directly from Maxwell’s equations. This approach ensures that the interaction between the gain medium and the optical field is determined by the actual device geometry and refractive index distribution.

The optical modes of the laser cavity were analyzed using the Eigenfrequency Study in the Wave Optics Module of COMSOL Multiphysics or FDTD (Finite-Difference Time-Domain)

solver on Lumeical to solve the Maxwell equations and obtain the resonant eigenmodes of the structure.

In the absence of free charges and currents, Maxwell's equations are written as

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \quad (3.1)$$

$$\nabla \times H = \varepsilon_r(\mathbf{r}) \frac{\partial E}{\partial t} \quad (3.2)$$

where $\varepsilon_r(\mathbf{r})$ denotes the spatially varying permittivity defined by the epitaxial layer stack and cavity structure. Assuming time-harmonic solutions of the form $E(\mathbf{r}, t) = E(\mathbf{r})e^{-i\omega t}$ the wave equation reduces to the eigenvalue problem

$$\nabla \times (\nabla \times E) = \left(\frac{\omega}{c}\right)^2 n^2(\mathbf{r})E(\mathbf{r}) \quad (3.3)$$

where $n(\mathbf{r})$ is the refractive index distribution and ω represents the angular eigenfrequency of the optical mode. Solving this equation under appropriate boundary conditions yields a discrete set of eigenfrequencies ω_m and corresponding mode profiles $E_m(\mathbf{r})$.

For edge-emitting Fabry–Perot and distributed feedback lasers, the eigenvalue problem reduces to guided-mode analysis in the transverse cross-section, from which propagation constants and transverse field distributions are obtained. In contrast, vertical-cavity surface-emitting lasers require simultaneous consideration of longitudinal resonance and transverse confinement due to their short cavity length and distributed Bragg reflector boundaries. Despite these geometric differences, the underlying eigenvalue formulation remains identical, ensuring a consistent treatment across architectures.

Once the fundamental mode profile $E_0(\mathbf{r})$ is determined, the optical confinement factor is evaluated directly from the spatial field distribution as[13]

$$\Gamma = \frac{\int_{\text{active}} |E(\mathbf{r})|^2 d\mathbf{r}}{\int_{\text{total}} |E(\mathbf{r})|^2 d\mathbf{r}} \quad (3.4)$$

This definition quantifies the fraction of modal electromagnetic energy residing within the gain region. Because Γ is derived from the actual eigenmode solution, it inherently accounts for

active-layer thickness, vertical placement, lateral confinement, and refractive index contrast. In strongly confined cavities such as VCSELs, even small geometric modifications can significantly alter the confinement factor, making eigenmode-based evaluation essential for reliable modeling.

In addition to spatial confinement, temporal confinement of the optical field is characterized by the cavity quality factor and photon lifetime. The quality factor is defined as

$$Q = \omega_0 \frac{U}{P_{loss}} \quad (3.5)$$

where U is the total stored electromagnetic energy and P_{loss} is the power dissipated per optical cycle. The corresponding photon lifetime is given by

$$\tau_p = \frac{Q}{\omega_0} \quad (3.6)$$

In travelling-wave formulations, this quantity can equivalently be expressed in terms of group velocity v_g and distributed losses as

$$\tau_p = \frac{1}{v_g(\alpha_i + \alpha_m)} \quad (3.7)$$

where α_i represents internal loss and α_m denotes mirror loss. The photon lifetime determines the temporal decay of the cavity field and directly influences threshold and modulation response.

For highly confined structures, the spatial extent of the optical mode is further characterized by the effective mode volume, defined as

$$V_{eff} = \frac{\iiint \epsilon_r(\mathbf{r}) |E(\mathbf{r})|^2 d\mathbf{r}}{\max[\epsilon_r(\mathbf{r}) |E(\mathbf{r})|^2]} \quad (3.8)$$

The effective mode volume provides a quantitative measure of how tightly the optical field is localized within the cavity. In vertical-cavity geometries, where longitudinal confinement is extreme, V_{eff} becomes a critical parameter influencing differential gain, spontaneous emission coupling, and dynamic response.

Through this eigenmode analysis, the framework extracts the spatial field distribution, confinement factor, photon lifetime, and effective mode volume directly from the physical device structure. These quantities establish a rigorous optical foundation for subsequent electronic-

structure and time-domain simulations, ensuring that gain–mode interaction is evaluated using physically consistent confinement parameters rather than empirical approximations.

3.3 Eight-band k.p model

3.3.1 Strain Distribution

This section summarizes the main approaches used to evaluate strain fields in semiconductor nanostructures. Strain is a critical factor in epitaxially grown quantum dots (QDs). When a thin epitaxial layer is deposited on a substrate with a different lattice constant, the film initially grows in a two-dimensional manner. Once the deposited layer exceeds a material-dependent critical thickness, three-dimensional islands spontaneously form in order to reduce strain energy. This growth mechanism—driven by lattice mismatch between the film and substrate—is known as the Stranski–Krastanow (SK) mode [111]. The lattice mismatch can be expressed as

$$\varepsilon_0 = \frac{a_{\text{deposited}} - a_{\text{substrate}}}{a_{\text{deposited}}}, \quad (3.9)$$

where ε_0 is the initial strain and a denotes the intrinsic lattice constant.

Two major categories of numerical techniques are used to obtain the strain-induced displacement field in QD systems[112]: (1) atomistic methods, such as the valence force field (VFF) model, and (2) continuum approaches, typically referred to as classical elasticity (CM).

VFF explicitly accounts for interatomic potentials and is well suited for atomistic simulations, but its computational cost becomes prohibitive for the large simulation domains considered here, particularly because our strain workflow involves several nested calculations [113], [114]. Consequently, the continuum elasticity formalism is adopted in this work.

Within CM, several numerical strategies have been reported, including the Green’s function approach [115], two-dimensional Fourier-space Green’s function formulations [116], and the widely used finite element method (FEM) [117], [118]. Because the first two approaches can be regarded as simplified variants of FEM, FEM offers the most flexibility and accuracy for our three-dimensional problem and is therefore selected.

FEM discretizes the simulation domain into a mesh of elements and nodes. The displacement field is obtained by minimizing the total strain energy, written as

$$U_{\text{strain}} = \frac{1}{2} \sum \sigma \varepsilon, \quad (3.10)$$

where σ and ε are the stress and strain tensors. The strain tensor components are related to the nodal displacements u, v, w through the standard kinematic relations:

$$\varepsilon = \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{pmatrix} = \begin{pmatrix} \partial u / \partial x \\ \partial v / \partial y \\ \partial w / \partial z \\ (\partial u / \partial y + \partial v / \partial x) / 2 \\ (\partial v / \partial z + \partial w / \partial y) / 2 \\ (\partial w / \partial x + \partial u / \partial z) / 2 \end{pmatrix}. \quad (3.11)$$

The stress tensor follows Hooke's law,

$$\sigma = E(\varepsilon - \varepsilon_0) + \sigma_0, \quad (3.12)$$

where $\mathbf{E}$ is the stiffness matrix. For cubic crystals, the elastic tensor takes the form

$$E = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{pmatrix}, \quad (3.13)$$

here C_{11} , C_{12} , and C_{44} are elasticity moduli. Thus, the strain energy U_{strain} can be given in the form only related to strain tensors and elasticity moduli. Minimization of Eq. (3.4) yields the displacement field and therefore the strain distribution throughout the nanostructure.

3.3.2 Piezoelectric Potential

For the local symmetry of the atomic lattice, in unstrained bulk crystals the net polarization is zero, but in strongly strained nanostructures—such as QDs—the atomic displacements produce non-zero polarization and bound charge.

Early studies of quantum wells and QDs included only the first-order (linear) piezoelectric term [112], [119]. Later work by Bester *et al.* demonstrated that second-order (quadratic) terms are of

comparable magnitude [120], prompting their inclusion in subsequent modeling studies [121]. Although the resulting PZT potential is typically only a few meV, its quadrupole-like symmetry reduces the point-group symmetry of QDs (e.g., from C_{4v} or $C_{\infty v}$ to C_{2v}), which can modify optical selection rules and contribute to spin-dependent energy splitting. For these reasons, both linear and quadratic PZT terms are included in this study.

The linear polarization is expressed as

$$P_1 = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 2e_{14} & 0 & 0 \\ 0 & 2e_{14} & 0 \\ 0 & 0 & 2e_{14} \end{pmatrix} \begin{pmatrix} \varepsilon_{yz} \\ \varepsilon_{xz} \\ \varepsilon_{xy} \end{pmatrix}, \quad (3.14)$$

and the quadratic component is

$$P_2 = 2B_{114} \begin{pmatrix} \varepsilon_{xx}\varepsilon_{yz} \\ \varepsilon_{yy}\varepsilon_{xz} \\ \varepsilon_{zz}\varepsilon_{xy} \end{pmatrix} + 2B_{124} \begin{pmatrix} \varepsilon_{yz}(\varepsilon_{yy} + \varepsilon_{zz}) \\ \varepsilon_{xz}(\varepsilon_{xx} + \varepsilon_{zz}) \\ \varepsilon_{xy}(\varepsilon_{xx} + \varepsilon_{yy}) \end{pmatrix} + 4B_{156} \begin{pmatrix} \varepsilon_{xz}\varepsilon_{xy} \\ \varepsilon_{yz}\varepsilon_{xy} \\ \varepsilon_{yz}\varepsilon_{xz} \end{pmatrix}, \quad (3.15)$$

with e_{14} , B_{114} , B_{124} , and B_{156} being the linear and quadratic piezoelectric coefficients.

The polarization-induced charge density is

$$\rho_p(\mathbf{r}) = -\nabla \cdot (P_1 + P_2). \quad (3.16)$$

and the resulting PZT potential V_p is obtained by solving Poisson's equation:

$$\rho_p(\mathbf{r}) = \epsilon_0 \nabla \cdot (\epsilon_s(\mathbf{r}) \cdot \nabla V_p(\mathbf{r})), \quad (3.17)$$

where ϵ_0 is the vacuum permittivity and ϵ_s the static dielectric constant.

3.3.3 Electronic Band Structure

Although ab-initio approaches such as density functional theory (DFT) provide parameter-free accuracy for bulk materials, their computational cost remains prohibitive for realistically sized QDs. Therefore, nanostructure modeling typically relies on semi-empirical techniques using experimentally determined parameters such as effective masses and deformation potentials. Common approaches include tight-binding (TB) [122], [123], empirical pseudopotential (EP) methods [124], and various forms of the $k \cdot p$ formalism [93], [125], [126].

The $k \cdot p$ method is particularly suitable for III–V semiconductors with small band gaps, as it provides a systematic way to incorporate strain-induced coupling between conduction and valence bands. Starting from the single-particle Schrödinger equation

$$H\Psi(\mathbf{r}) = \left(\frac{p^2}{2m_0} + V(\mathbf{r}) \right) \Psi(\mathbf{r}) = E\Psi(\mathbf{r}), \quad (3.18)$$

where $p = -i\hbar\nabla$ is momentum operator, $V(\mathbf{r})$ is periodic potential of lattice. According to the Bloch's theorem, the wavefunction $\Psi_{nk}(\mathbf{r})$ can be written in the form of Bloch wave $e^{ik \cdot \mathbf{r}} u_{nk}(\mathbf{r})$ in the lattice, therefore it can be derived as

$$\left(\frac{p^2}{2m_0} + \frac{\hbar^2 k^2}{2m_0} + \frac{\hbar \mathbf{k} \cdot \mathbf{p}}{m_0} + V(\mathbf{r}) \right) u_{nk}(\mathbf{r}) = E u_{nk}(\mathbf{r}), \quad (3.19)$$

and the terms consisting of the wavevector k are the perturbations. At the most-attractive Γ -point $k = 0$, the isotropic effective mass of electron in bulk m_e^* can be evaluated by fitting the measured bandgap E_g , giving

$$\frac{m_0}{m_e^*} = (1 + F) + \frac{E_p(E_g + 2\Delta/3)}{E_g(E_g + \Delta)}, \quad (3.20)$$

where F is Kane parameter for remote band contributions to the conduction band, Δ is the spin-orbit (SO) splitting energy. Correspondingly, the obtained effective mass can be utilized to calculate the energy E_n as well as the wavefunction approximation u_n by Eq. 3.13 at Γ -point in the nano-sized heterostructure with a specific 3D confinement potential $V(\mathbf{r})$.

TB is based on the assumption that the electrons are tightly bound to the atoms, and all isolated atoms have distinct orbitals. The total status of the solid is described by the energies of carriers in each individual orbital and the process of electrons hopping between orbitals at different atoms. Different from the $k \cdot p$ formalism which based on the symmetry properties of the Bloch functions in the conduction and valence bands [127], TB enables to take into consideration the possible atomic inequality of crystal facet in different orientations, as every atom is accounted for separately in TB model.

EP is something in the middle between the $k \cdot p$ and TB. On the one hand, EP aims to solve the structural asymmetry problem which $k \cdot p$ fails to address, when the atomistic effect becomes

significant; on the other hand, EP is better at dealing with the wavefunctions compared with TB. EP simplifies the calculation of band structure itself: only one-band Schrödinger equation is solved; simultaneously, the underlying atomic effect of lattice is included when dealing with the confinement potential part:

$$V(\mathbf{r}) = \sum_{j,\alpha} v_j(|\mathbf{r} - \mathbf{R}_{j,\alpha}|), \quad (3.21)$$

where the index j runs over all atoms in the unit cell and v_j are the atomic potentials centered at the atomic sites $\mathbf{R}_j$ of atom type α .

Because FEM and continuum elasticity are used for strain calculations, the $k \cdot p$ method integrates most naturally with our framework. Additionally, previous work has shown that atomistic asymmetry has negligible influence for the structures of interest [128]. Therefore, an eight-band $k \cdot p$ Hamiltonian is adopted, incorporating one conduction band and three valence bands with spin degeneracy.

The total Hamiltonian is written as

$$H = H_k + H_s + V_p, \quad (3.22)$$

where H_k is the unstrained Hamiltonian, in which the main diagonal terms describe the kinetic energy of particle and potential profile of corresponding bands, while the off-diagonal terms describe the interaction and coupling between the bands, giving:

$$H_k = \begin{pmatrix} A & 0 & V^\dagger & 0 & \sqrt{3}V & -\sqrt{2}U & -U & \sqrt{2}V^\dagger \\ 0 & A & -\sqrt{2}U & -\sqrt{3}V^\dagger & 0 & -V & \sqrt{2}V & U \\ V & -\sqrt{2}U & -P + Q & -S^\dagger & R & 0 & \sqrt{3/2}S & -\sqrt{2}Q \\ 0 & -\sqrt{3}V & -S & -P - Q & 0 & R & -\sqrt{2}R & \sqrt{1/2}S \\ \sqrt{3}V^\dagger & 0 & R^\dagger & 0 & -P - Q & S^\dagger & \sqrt{1/2}S^\dagger & \sqrt{2}R^\dagger \\ -\sqrt{2}U & -V^\dagger & 0 & R^\dagger & S & -P + Q & \sqrt{2}Q & \sqrt{3/2}S^\dagger \\ -U & \sqrt{2}V^\dagger & \sqrt{3/2}S^\dagger & -\sqrt{2}R^\dagger & \sqrt{1/2}S & \sqrt{2}Q & -P - \Delta & 0 \\ \sqrt{2}V & U & -\sqrt{2}Q & \sqrt{1/2}S^\dagger & \sqrt{2}R & \sqrt{3/2}S & 0 & -P - \Delta \end{pmatrix}, \quad (3.23)$$

Where

$$A = E_c - \frac{\hbar^2}{2m_e^*} (\partial_x^2 + \partial_y^2 + \partial_z^2) \quad (3.24)$$

$$P = -E_v - \frac{\hbar^2}{2m_0} \gamma_1 (\partial_x^2 + \partial_y^2 + \partial_z^2) \quad (3.25)$$

$$Q = -\frac{\hbar^2}{2m_0} \gamma_2 (\partial_x^2 + \partial_y^2 - 2\partial_z^2) \quad (3.26)$$

$$R = \sqrt{3} \frac{\hbar^2}{2m_0} [\gamma_2 (\partial_x^2 - \partial_y^2) - 2i\gamma_3 \partial_x \partial_y] \quad (3.27)$$

$$S = -\sqrt{3} \gamma_3 \partial_z (\partial_x - i\partial_y) \quad (3.28)$$

$$U = \frac{-i}{3} P_0 \partial_z \quad (3.29)$$

$$V = \frac{-i}{\sqrt{6}} P_0 (\partial_x - i\partial_y) \quad (3.30)$$

The Luttinger parameters are calculated by

$$\gamma_1 = \gamma_1^L - \frac{E_p}{3E_g + \Delta} \quad (3.31)$$

$$\gamma_2 = \gamma_2^L - \frac{1}{2} \frac{E_p}{3E_g + \Delta} \quad (3.32)$$

$$\gamma_3 = \gamma_3^L - \frac{1}{2} \frac{E_p}{3E_g + \Delta} \quad (3.33)$$

$$E_p = \frac{2m_0 P_0^2}{\hbar^2} \quad (3.34)$$

where E_c and E_v are conduction band edge (CBE) and valence band edge (VBE), respectively; $E_g = E_c - E_v$ is the energy band gap. The matrix element P_0 can be calculated by given band parameter E_p obtained by experiments.

H_s is the strained Hamiltonian, defined as

$$H_s = \begin{pmatrix} a_c \varepsilon_h & 0 & -v^\dagger & 0 & -\sqrt{3}v & \sqrt{2}u & u & -\sqrt{2}v^\dagger \\ 0 & a_c \varepsilon_h & \sqrt{2}u & \sqrt{3}v^\dagger & 0 & v & -\sqrt{2}v & -u \\ -v & \sqrt{2}u & -p+q & -s^\dagger & r & 0 & \sqrt{3/2}s & -\sqrt{2}q \\ 0 & \sqrt{3}v & -s & -p-q & 0 & r & -\sqrt{2}r & \sqrt{1/2}s \\ -\sqrt{3}v^\dagger & 0 & r^\dagger & 0 & -p-q & s^\dagger & \sqrt{1/2}s^\dagger & \sqrt{2}r^\dagger \\ \sqrt{2}u & v^\dagger & 0 & r^\dagger & s & -p+q & \sqrt{2}q & \sqrt{3/2}s^\dagger \\ u & -\sqrt{2}v^\dagger & \sqrt{3/2}s^\dagger & -\sqrt{2}r^\dagger & \sqrt{1/2}s & \sqrt{2}q & -p & 0 \\ -\sqrt{2}v & -u & -\sqrt{2}q & \sqrt{1/2}s^\dagger & \sqrt{2}r & \sqrt{3/2}s & 0 & -p \end{pmatrix}, \quad (3.35)$$

Where,

$$\varepsilon_h = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} \quad (3.36)$$

$$\varepsilon_b = \varepsilon_{zz} - \frac{\varepsilon_{xx} + \varepsilon_{yy}}{2} \quad (3.37)$$

$$p = a_v \varepsilon_h \quad (3.38)$$

$$q = b \varepsilon_b$$

$$r = \frac{\sqrt{3}}{2} b (\varepsilon_{xx} - \varepsilon_{yy}) - i d \varepsilon_{xy} \quad (3.39)$$

$$s = -d (\varepsilon_{xz} - i \varepsilon_{yz}) \quad (3.40)$$

$$u = \frac{-i}{\sqrt{3}} P_0 (\varepsilon_{xz} \partial_x + \varepsilon_{yz} \partial_y + \varepsilon_{zz} \partial_z) \quad (3.41)$$

$$v = \frac{-i}{\sqrt{6}} P_0 [(\varepsilon_{xx} - i \varepsilon_{xy}) \partial_x + (\varepsilon_{xy} - i \varepsilon_{yy}) \partial_y + (\varepsilon_{xz} - i \varepsilon_{yz}) \partial_z] \quad (3.42)$$

V_p is the additional PZT effect, giving

$$V_p = \begin{pmatrix} -V_p & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -V_p & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & V_p & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & V_p & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & V_p & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & V_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & V_p & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & V_p \end{pmatrix} \quad (3.43)$$

where V_p is the PZT potential derived by Eq. (3.17). Note the signs for conduction band and valence band are reversed, since the electrons and holes flux in these two bands are with opposite electric charges.

3.3.4 Light–Matter Interaction and Interband Transition Rate

The interaction between the optical field and the electronic states of the QD/Qdash gain medium is described using a two-level approximation. Consider a transition between an initial state n and a final state m . The time-dependent wavefunction of the system can be expressed as a coherent superposition of the two states [129],

$$\psi_{nm}(r, t) = a \psi_m(\mathbf{r}, t) + b \psi_n(\mathbf{r}, t) \quad (3.44)$$

$$a^2 + b^2 = 1 \quad (3.45)$$

If the system initially occupies the lower-energy state n , the initial condition is $a = 0$, $b = 1$. In the presence of a time-varying optical perturbation, the system evolves into a superposition of the two states, and the probability density $|\psi_{nm}(\mathbf{r}, t)|^2$ develops an oscillatory component at the optical angular frequency ω . This oscillatory behavior reflects coherent population transfer between the two levels. When the optical frequency matches the transition frequency $\omega_{nm} = (E_m - E_n)/\hbar$, resonant absorption occurs and the system is driven toward the excited state m . The periodic exchange of population between the two states is commonly referred to as Rabi oscillation, while photon absorption remains a statistical process governed by transition probabilities.

The interaction between the electronic system and the optical field is described by a time-dependent perturbation Hamiltonian. Introducing the electromagnetic vector potential $\mathbf{A}_0(\mathbf{r}, t)$, the perturbation term is written as

$$H_{nm} = -\frac{e}{m_0} A_0(\mathbf{r}, t) \mathbf{e} \cdot \mathbf{p}, \quad (3.46)$$

where e is the electron charge, m_0 is the free-electron mass, and $\mathbf{p}$ is the momentum operator. The electric field is related to the vector potential through:

$$\mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{A}_0}{\partial t}. \quad (3.47)$$

Assuming a monochromatic optical field polarized along the unit vector $\mathbf{e}$, the electric field is expressed as

$$\mathbf{E} = \mathbf{e} \sqrt{\frac{2\hbar\omega}{\eta\epsilon_0\Omega}} (e^{i\omega t} + e^{-i\omega t}), \quad (3.48)$$

where η is the refractive index and Ω is the system volume.

From the perturbation Hamiltonian and field representation, the transition strength is characterized by

$$|H_{nm}|^2 = \left[\frac{eA_0(\mathbf{r})}{2m_0} \right]^2 |M|^2 = \frac{e^2\hbar}{2\omega\eta\epsilon_0m_0^2\Omega} |M|^2, \quad (3.49)$$

where the momentum matrix element is defined as

$$M = \langle m | \mathbf{e} \cdot \mathbf{p} | n \rangle = \int \psi_m^\dagger \mathbf{e} \cdot \mathbf{p} \psi_n d\mathbf{r}. \quad (3.50)$$

Using Fermi's Golden Rule, the interband transition rate is given by:

$$W = \frac{\pi e^2}{\omega \eta \epsilon_0 m_0^2 \Omega} |M|^2 \delta(\hbar \omega_{nm} - \hbar \omega), \quad (3.51)$$

The absorption coefficient, defined as the number of photons absorbed per unit propagation distance, follows as

$$\alpha(\hbar \omega) = \frac{\pi e^2}{c \omega \eta \epsilon_0 m_0^2 \Omega} |M|^2 \delta(\hbar \omega_{nm} - \hbar \omega), \quad (3.52)$$

In practical systems, the delta function is broadened due to lifetime and inhomogeneous effects. It is commonly replaced by a Lorentzian lineshape to account for finite linewidth of the transition.

To obtain a physically transparent expression for the transition matrix element, the total wavefunction is separated into an envelope function $F(\mathbf{r})$ and a periodic Bloch function $u(\mathbf{r})$. Substituting this decomposition into the matrix element yields

$$|M|^2 = |\langle F_m | F_n \rangle \langle u_m | \mathbf{e} \cdot \mathbf{p} | u_n \rangle + \langle u_m | u_n \rangle \langle F_m | \mathbf{e} \cdot \mathbf{p} | F_n \rangle|^2. \quad (3.53)$$

For interband transitions, the orthogonality of Bloch functions ensures $\langle u_m | u_n \rangle = 0$, eliminating the second term. The matrix element therefore reduces to

$$|M|^2 = |I_{mn}|^2 |M_{mn}|^2, \quad (3.1)$$

where

$$I_{mn} = \sum_i F_m^\dagger(\mathbf{r}_i) F_n(\mathbf{r}_i), \quad (3.55)$$

The envelope-function overlap I_{mn} depends strongly on nanostructure geometry and spatial confinement. It also embodies optical selection rules, as interband transitions are allowed only between states belonging to the same irreducible symmetry class (e.g., $s \rightarrow s$, $p \rightarrow p$).

An equivalent expression for the absorption coefficient can be written in terms of the dipole matrix element,

$$\alpha(\hbar \omega) = \frac{\omega \pi}{c \eta \epsilon_0 \Omega} |d_{mn}|^2 \delta(\hbar \omega_{nm} - \hbar \omega), \quad (3.56)$$

where

$$|d_{mn}|^2 = \frac{e^2 |M|^2}{\omega^2 m_0^2} \quad (3.57)$$

This dipole formulation is frequently used in gain calculations, as it directly relates transition strength to optical polarization.

Through this formulation, the microscopic transition properties derived from the 8-band $k \cdot p$ model are translated into absorption and gain coefficients. These quantities form the material-level input to the travelling-wave time-domain laser model presented in the next section.

3.4 Time-domain traveling wave model

Time-domain modeling is particularly well suited for active photonic devices where the optical field interacts strongly with the carrier population, such as semiconductor diode lasers. For QD lasers, the TDTW framework is widely adopted because it naturally incorporates longitudinal field propagation, carrier dynamics, and spontaneous emission.

The longitudinal evolution of the transverse-electric (TE) guided mode inside the cavity is governed by the second-order wave equation [97]:

$$\frac{\partial^2 E(z, t)}{\partial z^2} - \frac{n_b^2}{c^2} \mu_0 \frac{\partial^2 E(z, t)}{\partial t^2} = \mu_0 \frac{\partial^2 P(z, t)}{\partial t^2} + \mu_0 \frac{\partial J_{sp}(z, t)}{\partial t} \quad (3.58)$$

where n_b is the background effective index, μ_0 is the permeability of free space, E is the optical field amplitude, P represents the polarization of the QD medium, and J_{sp} accounts for the spontaneous-emission-related current source.

Under the slowly varying envelope approximation, the optical field is written as the sum of forward- and backward-propagating components:

$$E(z, t) = E^+(z, t)e^{-i(\omega_0 t - k_0 z)} + E^-(z, t)e^{-i(\omega_0 t + k_0 z)} \quad (3.59)$$

where ω_0 and k_0 are a chosen reference frequency and wave vector. The powers carried by these envelopes in a given cavity section are denoted P^+ and P^- .

To solve Eq. (3.58) numerically, the induced polarization P and the spontaneous-emission current source J_{sp} must be approximated in a manner consistent with QD physics.

The active region is modeled as a four-level QD system comprising the ground state (GS), excited state (ES), wetting-layer (WL) edge, and the lowest states of the separate-confinement heterostructure (SCH). Only the first ES is included, following a simplified but widely adopted model. Carrier relaxation is assumed to occur only through downward cascaded processes.

To capture inhomogeneous broadening arising from the statistical distribution of QD sizes, the QD ensemble is partitioned into N subpopulations. QDs within each subpopulation are treated as identical and therefore share the same transition energies $E_{m,i}$ and occupation probabilities $f_{m,i}$ for GS/ES states ($m = \text{GS or ES}$).

A Gaussian distribution is assumed for the QD size dispersion, resulting in the following existence probability for the i -th group:

$$G_i = \frac{1}{Z} \exp \left(-4 \ln 2 \times \frac{(\hbar \bar{\omega}_{i,GS} - \hbar \bar{\omega}_{(N+1)/2,GS})^2}{\Delta E^2} \right) \quad (3.60)$$

where σ is the full width at half maximum (FWHM)-related parameter and Z normalizes the distribution.

The total polarization is related to the ensemble susceptibility:

$$P(z, t) = \varepsilon_0 \int_{-\infty}^t \chi(\{\rho_{im}\}, t - \tau) E(z, \tau) d\tau \quad (3.61)$$

where χ depends on the occupation probabilities $\{\rho_{im}\}$ and incorporates inhomogeneous broadening effects.

The spontaneous emission source is expressed as

$$S(z, t) = \frac{1}{2} \sqrt{\frac{\mu_0 \omega_0}{k_0}} J_s \times e^{-j\omega_0 t} \quad (3.62)$$

where each term contributes noise to the guided mode.

The resulting coupled wave equations for the envelopes are

$$\frac{\eta}{c} \frac{\partial E^\pm}{\partial t} \pm \frac{\partial E^\pm}{\partial z} = -\frac{\alpha_i}{2} E^\pm(z, t) + S^\pm(z, t) - jP^\pm(z, t) \quad (3.63)$$

where α_i is the internal loss, $E^\pm$, $S^\pm$, $P^\pm$ are electric field amplitude, spontaneous emission noise source and the optical susceptibility of the QD active medium, respectively. Here, the expressions of $S^\pm(z, t)$ and $P^\pm(z, t)$ are given as the sum of single GS and ES contributions from each QD population:

$$P^\pm(z, t) = \sum_{i=1}^N \sum_{m=GS,ES} P_{im}^\pm(z, t) = \sum_{i=1}^N \sum_{m=GS,ES} \left[\frac{j}{\hbar} \frac{\omega_0}{2\pi c \eta} \frac{\Gamma_{xy}}{h_W} N_D G_i D_m (2\rho_{im}(z, t) - 1) \times \int_{-\infty}^t e^{j(\bar{\omega}_{i,m} - \omega_0)(t-\tau)} e^{-\Gamma(t-\tau)} E^\pm(z, t) d\tau \right] \quad (3.64)$$

$$S^\pm(z, t) \Delta z = \sum_{i=1}^N \sum_{m=GS,ES} \left[\Gamma \sqrt{\frac{\hbar \bar{\omega}_{i,m} \beta_{sp} N_{im}(z, t)}{\pi \Gamma \Delta t 2\tau_m^{sp}}} \times \int_{-\infty}^t e^{j(\bar{\omega}_{i,m} - \omega_0)(t-\tau)} e^{-\Gamma(t-\tau)} e^{j\varphi_{im}(z, \tau)} d\tau \right] \quad (3.65)$$

Where Γ_{xy} is the field confinement factor in the QD layers, h_W is the QW width, $1/\Gamma$ represents the characteristic dephasing time of the interband transition, β_{sp} is the spontaneous emission factor describing the coupling between the spontaneously emitted radiation and the waveguide mode, $\varphi_{im}(z, t)$ is a set of independent random phase contributions uniformly distributed between 0 and 2π and completely uncorrelated both in time and space. and $N_{im}(z, t)$ represents the total number of carriers occupying the m th state in QDs belonging to the i th population and lying within the longitudinal slice of the cavity.

$$N_{im}(z, t) = N_l N_D G_i D_m \rho_{im}(z, t) W \Delta z \quad (3.66)$$

where W is the ridge width, D_{QD} the areal QD density, D_m is the degeneracy of the m th QD state and n_l is the number of QD layers.

For a Fabry-Pérot (FP) cavity, the boundary conditions are

$$E^+(0, t) = \sqrt{R_l} E^-(0, t) \quad (3.67)$$

$$E^-(L, t) = \sqrt{R_r} E^+(L, t) \quad (3.68)$$

here R_l and R_r are the facet reflectivities and L is the cavity length.

Carrier dynamics within the active region are described by a set of coupled rate equations, (Fig.3.2) one each for SCH and WL carriers, and two for the GS and ES populations of every QD sub-ensemble. These equations are solved in every longitudinal section of the device under current injection:

$$\frac{dN_{SCH}}{dt} = \eta_i \frac{J}{e} \Delta z W - \frac{N_{SCH}}{\tau_r^{SCH}} - \frac{N_{SCH}}{\tau_c^{WL}} + \frac{N_{WL}}{\tau_e^{WL}} \quad (3.69)$$

$$\frac{dN_{WL}}{dt} = \frac{N_{SCH}}{\tau_c^{WL}} - \frac{N_{WL}}{\tau_r^{WL}} - \frac{N_{WL}}{\tau_e^{WL}} - \sum_{i=1}^N \frac{G_i}{\tau_c^{ES}} N_{WL} (1 - \rho_{i,ES}) + \sum_{i=1}^N \frac{N_{i,ES}}{\tau_e^{ES}} \quad (3.70)$$

$$\begin{aligned} \frac{dN_{i,ES}}{dt} = & \frac{G_i}{\tau_c^{ES}} N_{WL} (1 - \rho_{i,ES}) + \frac{N_{i,GS}}{\tau_e^{GS}} (1 - \rho_{i,ES}) - \frac{N_{i,ES}}{\tau_e^{ES}} - \frac{N_{i,ES}}{\tau_s^{ES}} - \frac{N_{i,ES} \rho_{i,ES}}{\tau_{Au}^{ES}} \\ & - \frac{N_{i,ES}}{\tau_c^{GS}} (1 - \rho_{i,GS}) - \frac{j \Delta z}{\hbar \bar{\omega}_{i,ES}} \left[(E^+ p_{i,ES}^{+*} - E^{+*} p_{i,ES}^+) + (E^- p_{i,ES}^{-*} - E^{-*} p_{i,ES}^-) \right] \end{aligned} \quad (3.71)$$

$$\begin{aligned} \frac{dN_{i,GS}}{dt} = & \frac{N_{i,ES}}{\tau_c^{GS}} (1 - \rho_{i,GS}) - \frac{N_{i,GS}}{\tau_e^{GS}} (1 - \rho_{i,ES}) - \frac{N_{i,GS}}{\tau_s^{GS}} - \frac{N_{i,GS} \rho_{i,GS}}{\tau_{Au}^{GS}} \\ & - \frac{j \Delta z}{\hbar \bar{\omega}_{i,GS}} \left[(E^+ p_{i,GS}^{+*} - E^{+*} p_{i,GS}^+) + (E^- p_{i,GS}^{-*} - E^{-*} p_{i,GS}^-) \right] \end{aligned} \quad (3.72)$$

where J is the applied current density, along with QD ridge width W to represent the input excitation; η_i is the internal quantum efficiency; N_{WL} and N_{SCH} are the total number of carriers in WL and SCH respectively; the total number of carriers in GS and ES are $N_{i,GS}$ and $N_{i,ES}$ in i^{th} QD group, respectively; and the corresponding occupation probabilities of GS and ES in i^{th} QD group are $\rho_{i,GS}$ and $\rho_{i,ES}$, respectively; the microscopic polarizations of GS and ES in i^{th} QD group are $p_{i,GS}^{\pm}$ and $p_{i,ES}^{\pm}$ respectively, which contribute to the total polarization $P^{\pm}$ (the detailed

expressions can be found in Eq. (3.64)); and the last term of Eq. (3.71) and (3.72) describes the radiative recombination in i^{th} QD group.

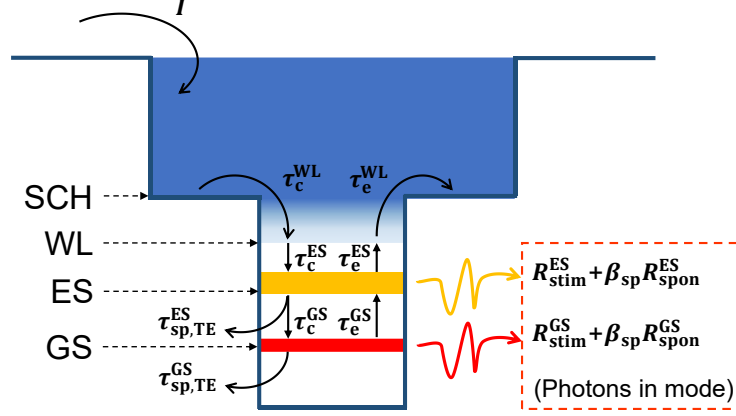


Figure 3.2 Schematic of carrier dynamics in a 4-level excitonic model of the active region of a typical QD laser [130].

The characteristic capture time τ_c^{WL} , τ_c^{ES} and τ_c^{GS} describe the carrier relaxation time from SCH to WL, from WL to ES within a QD and from ES to GS within a QD, respectively. The interband recombination time in WL and SCH is τ_r^{WL} , and τ_r^{SCH} , respectively. The spontaneous emission recombination time in ES and GS is τ_s^{ES} and τ_s^{GS} respectively. The Auger recombination time in ES and GS is τ_{Au}^{ES} and τ_{Au}^{GS} , respectively. The interband transition energy in ES and GS in the i^{th} QD group is $\hbar\bar{\omega}_{i,ES}$ and $\hbar\bar{\omega}_{i,GS}$, respectively.

The escape time: τ_e^{WL} , τ_e^{ES} and τ_e^{GS} are calculated from the capture time, and interband transition energy, to make sure the recovery of a quasi-equilibrium energy distribution.

$$\tau_e^{WL} = \tau_c^{WL} \frac{DOS_{WL} \cdot N_l}{DOS_{SCH} \cdot h_{SCH}} \exp\left(\frac{\Delta E_{SCH-WL}}{k_B T}\right) \quad (3.73)$$

$$\tau_e^{ES} = \tau_c^{ES} \frac{D_{ES} \cdot N_D}{DOS_{WL}} \exp\left(\frac{\Delta E_{WL-ES}}{k_B T}\right) \quad (3.74)$$

$$\tau_e^{GS} = \tau_c^{GS} \frac{D_{GS}}{D_{ES}} \exp\left(\frac{\hbar\bar{\omega}_{i,ES} - \hbar\bar{\omega}_{i,GS}}{k_B T}\right) \quad (3.75)$$

here ΔE_{SCH-WL} and ΔE_{WL-ES} are the energy difference between SCH and WL band edge and between WL band edge and the highest energy of ES, respectively.

In summary, an available model for QD-based FP laser is established by the time-domain traveling wave (TDTW) combined with a simplified four-level rate equations. Based on this theoretical model, several properties can be investigated, e.g., the gain profile, the relative intensity noise (RIN), the linewidth of emission of QD-based FP laser.

3.4.1 Rate Equations for Qdash

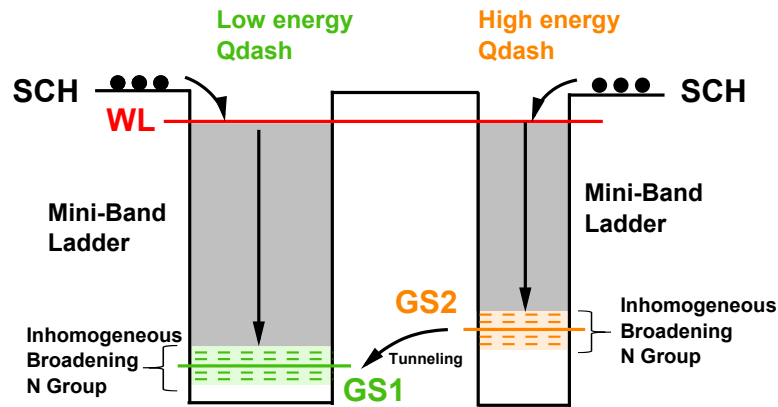


Figure 3.3 Schematic of carrier dynamics in lateral coupled Qdashes active region.

Because of the structural similarity between Qdash and Qdot, carrier-dynamics simulations for Qdash devices often reuse rate-equation models originally developed for Qdot. However, this approximation is insufficiently accurate. $k \cdot p$ calculations have shown that the band structure of Qdashes is fundamentally different from that of Qdot: instead of the well-separated ground-state (GS) and excited-state (ES) levels characteristic of a Qdot four-level system, Qdashes exhibit multiple closely spaced electronic states forming minibands between the GS and wetting-layer (WL) levels. The density of these intermediate states increases with dash length, and the strong lateral coupling inherent to elongated Qdashes makes in-plane tunneling and state coupling non-

negligible. The corresponding carrier relaxation and transport processes are illustrated in Fig. 4.1. To accurately capture these features, we revise the conventional model and formulate a modified set of rate equations, as presented below.

$$\frac{dN_{SCH}}{dt} = \eta_i \frac{J}{e} \Delta z W - \frac{N_{SCH}}{\tau_r^{SCH}} - \frac{N_{SCH}}{\tau_c^{WL}} + \frac{N_{WL}}{\tau_e^{WL}} \quad (3.76)$$

$$\begin{aligned} \frac{dN_{WL}}{dt} = & \frac{N_{SCH}}{\tau_c^{WL}} - \frac{N_{WL}}{\tau_r^{WL}} - \frac{N_{WL}}{\tau_e^{WL}} - \sum_{i=1}^N \frac{G_i}{\tau_c^{GS1}} N_{WL} (1 - \rho_{i,GS1}) - \sum_{i=1}^N \frac{G_i}{\tau_c^{GS2}} N_{WL} (1 - \rho_{i,GS2}) \\ & + \sum_{i=1}^N \frac{N_{i,GS1}}{\tau_e^{GS1}} + \sum_{i=1}^N \frac{N_{i,GS2}}{\tau_e^{GS2}} \end{aligned} \quad (3.77)$$

$$\begin{aligned} \frac{dN_{i,GS2}}{dt} = & \frac{G_i}{\tau_c^{GS2}} N_{WL} (1 - \rho_{i,GS2}) - \frac{N_{i,GS2}}{\tau_e^{GS2}} - \frac{N_{i,GS2}}{\tau_s^{GS2}} - \frac{N_{i,GS2} \rho_{i,GS2}}{\tau_{Au}^{GS2}} - \frac{N_{i,GS2}}{\tau_{tunneling}} (1 - \rho_{i,GS1}) \\ & - \frac{j\Delta z}{\hbar \bar{\omega}_{i,GS2}} [(E^+ p_{i,GS2}^{+*} - E^{+*} p_{i,GS2}^+) + (E^- p_{i,GS2}^{-*} - E^{-*} p_{i,GS2}^-)] \end{aligned} \quad (3.78)$$

$$\begin{aligned} \frac{dN_{i,GS1}}{dt} = & \frac{G_i}{\tau_c^{GS2}} N_{WL} (1 - \rho_{i,GS1}) - \frac{N_{i,GS1}}{\tau_e^{GS1}} - \frac{N_{i,GS1}}{\tau_s^{GS1}} - \frac{N_{i,GS1} \rho_{i,GS1}}{\tau_{Au}^{GS1}} + \frac{N_{i,GS2}}{\tau_{tunneling}} (1 - \rho_{i,GS1}) \\ & - \frac{j\Delta z}{\hbar \bar{\omega}_{i,GS1}} [(E^+ p_{i,GS1}^{+*} - E^{+*} p_{i,GS1}^+) + (E^- p_{i,GS1}^{-*} - E^{-*} p_{i,GS1}^-)] \end{aligned} \quad (3.79)$$

These equations describe carrier dynamics in the separate confinement heterostructure (SCH), the wetting layer (WL), and the Qdash sublevels (GS₁ and GS₂), with explicit inclusion of tunneling transfer between Qdashes. This addition allows us to accurately simulate the impact of lateral coupling on device performance.

To quantify the tunneling rate, Fermi's Golden Rule is employed. The transition probability per unit time is written as [131], [132]

$$P = \frac{4\pi}{\hbar} |\langle \Psi_j | V_{dash} - V_{barrier} | \Psi_i \rangle|^2 \delta(E_j - E_i) \quad (3.80)$$

where V_{dash} and $V_{barrier}$ denote the confinement potentials of the dash and surrounding barrier materials, respectively. The states Ψ_i and E_i represent the initial eigenstate envelope function and energy, while Ψ_j and E_j correspond to the final state.

The delta function enforces energy conservation during the tunneling process. In realistic systems, this condition is relaxed by lifetime broadening and phonon-assisted processes, allowing

finite tunneling probability even in the presence of moderate energy detuning. The effective tunneling rate can therefore be expressed as

$$P = \frac{1}{\tau_{\text{tunneling}}} \quad (3.81)$$

where $\tau_{\text{tunneling}}$ represents the characteristic carrier tunneling time between adjacent Qdashes which can be input into rate equations above.

3.4.2 TDTW model for single section mode-locked laser

To investigate the performance of a chirped QD stacked structure as a gain medium in a mode-locked laser the travelling-wave framework described above must be extended to include dispersive and nonlinear effects. The standard TDTW propagation equation is modified to account for group-velocity dispersion (GVD) and Kerr-induced self-phase modulation (SPM). The forward (+) and backward (-) propagating electrical field are expressed as Eq. (3.82) [133].

$$\begin{aligned} \pm \frac{\partial E^\pm(z, t)}{\partial z} + \frac{1}{v_g} \frac{\partial E^\pm(z, t)}{\partial t} - j \frac{\beta_2}{2} \frac{\partial^2 E^\pm(z, t)}{\partial t^2} = \\ - \frac{\alpha_i}{2} E^\pm(z, t) - j \delta |E(z, t)|^2 E^\pm(z, t) - j P^\pm(z, t) \\ + S^\pm(z, t) \end{aligned} \quad (3.82)$$

where the group velocity dispersion is included in the term $j \frac{\beta_2}{2} \frac{\partial^2 E^\pm(z, t)}{\partial t^2}$ and the effect of self-phase modulation is considered in the term $j \delta |E(z, t)|^2 E^\pm(z, t)$. The term $P^\pm(z, t)$ is polarization which is coupled with rate equations. The term $S^\pm(z, t)$ represents spontaneous emission noise. And the boundary conditions are

$$E^+(0, t) = r_R E^-(0, t) \quad (3.83)$$

$$E^-(L, t) = r_L E^+(L, t) \quad (3.84)$$

$$E^+(L, t) = \left(1 - \frac{s_0}{1 + \frac{|E^+(L, t)|^2}{I_{\text{sat}}}} \right) \quad (3.85)$$

where s_0 is unsaturated loss and I_{sat} is saturation intensity. r_R and r_L are reflectivity at $z = L$ (right) and $z = 0$ (left) facet respectively.

To consider the inhomogeneous broadening effect, the QDs are divided into N groups ($N=31$ in this study). Since the optical transition energies of the QDs in each layer of the chirped stacked structures are different, the weights of each group of QDs are described by a Gaussian mixture model.

$$G_i = \sum_{j=1}^M \frac{1}{A} \exp\left(-4\ln 2 \times \frac{(\hbar\omega_i - \hbar\omega_j)^2}{\Delta E^2}\right) \quad (3.86)$$

where i is the group number from 1 to N and $\hbar\omega_i$ is the corresponding ground state (GS) transition energy. Then, j is layer number from 1 to M and $\hbar\omega_j$ is the center transition energy of each layer. And A is a normalized constant such that $\sum_{i=1}^N G_i = 1$.

3.4.3 TDTW model for Qdash VCSEL

For vertical-cavity surface-emitting lasers, the travelling-wave formulation must be adapted to account for the standing-wave cavity formed by distributed Bragg reflectors (DBRs) and for the strong longitudinal index modulation. In the VCSEL case, the electric field is expressed as a superposition of forward and backward travelling envelopes modulating a central optical frequency [98], [134]:

$$E(r, z, t) = [E_+(z, t)e^{-j\beta_0 z} + E_-(z, t)e^{j\beta_0 z}]e^{j\omega_0 t}\psi_N(r) \quad (3.87)$$

where $\psi_N(r)$ represents the normalized transverse LP_{01} mode which can be obtained from optical eigen mode analysis. The slowly varying envelopes satisfy the regular one-dimensional travelling-wave equation Eq. (3.58).

Unlike edge-emitting devices, the VCSEL model must explicitly resolve propagation through each dielectric DBR layer, where refractive index and phase accumulation vary periodically along z .

The DBRs are treated through transfer-matrix boundary relations applied at every dielectric interface. The field amplitudes across an interface satisfy

$$\begin{pmatrix} E_+^{out} \\ E_-^{out} \end{pmatrix} = \begin{pmatrix} t_{11} & r_{12} \\ r_{21} & t_{22} \end{pmatrix} \begin{pmatrix} E_+^{in} e^{-j\phi} \\ E_-^{in} e^{-j\phi} \end{pmatrix} \quad (3.88)$$

where reflection and transmission coefficients t and r depend on adjacent effective refractive indices and $\phi = \pi/2$ accounts for quarter-wave DBR layers. At the top and bottom cavity boundaries, reflectivities are imposed as

$$E_-(z_{top}, t) = r_R E_+(z_{top}, t) \quad (3.89)$$

$$E_+(z_{bottom}, t) = r_L E_-(z_{bottom}, t) \quad (3.90)$$

Carrier dynamics is same as regular TDTW model, which are solved self-consistently with the travelling-wave equations. The stimulated recombination term couples photon density,

$$S(r, t) = \frac{\epsilon_0 n_{\text{eff}}^2}{2\omega_0} (|E_+|^2 + |E_-|^2) |\psi_N(r)|^2 \quad (3.91)$$

to the carrier equations, ensuring mutual feedback between optical field buildup and population inversion. Thermal effects are incorporated through current-dependent temperature rise, which modifies homogeneous broadening and escape rates. This formulation enables simulation of static light–current characteristics, turn-on dynamics, and modulation response of QD-VCSELs within a fully self-consistent spatiotemporal framework.

3.4.4 Numerical Implementation of the TDTW Model

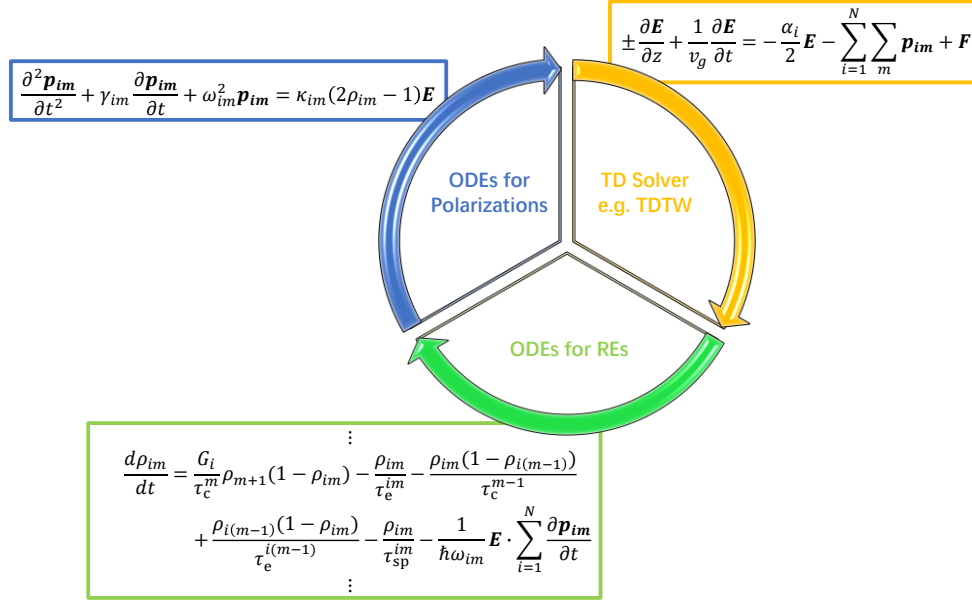


Figure 3.4 Sketch of calculation workflow of TDTW model [130].

The numerical implementation of the travelling-wave time-domain model follows a self-consistent coupled-ODE framework, as illustrated in Fig. 3.4 [130]. The optical field envelopes are propagated using a time-domain solver, while microscopic polarization equations describe the coherent light–matter interaction associated with interband transitions. In parallel, carrier reservoir equations govern population dynamics, including injection, spontaneous and non-radiative recombination, and interdash tunneling transport. These three components—field propagation, polarization dynamics, and carrier reservoirs—are solved simultaneously to ensure dynamic consistency between photon density and carrier occupation.

At each time step, the optical field update depends on the instantaneous polarization and carrier populations, while the polarization and reservoir equations are driven by the current field amplitude. This iterative coupling forms a closed dynamical system that captures both coherent

and incoherent processes within the cavity. By explicitly resolving polarization and carrier dynamics rather than inserting static gain expressions, the framework enables accurate simulation of transient response, modulation behavior, and noise characteristics in QD/Qdash laser devices.

3.5 Model Validation

3.5.1 Validation of optical eigenmode analysis

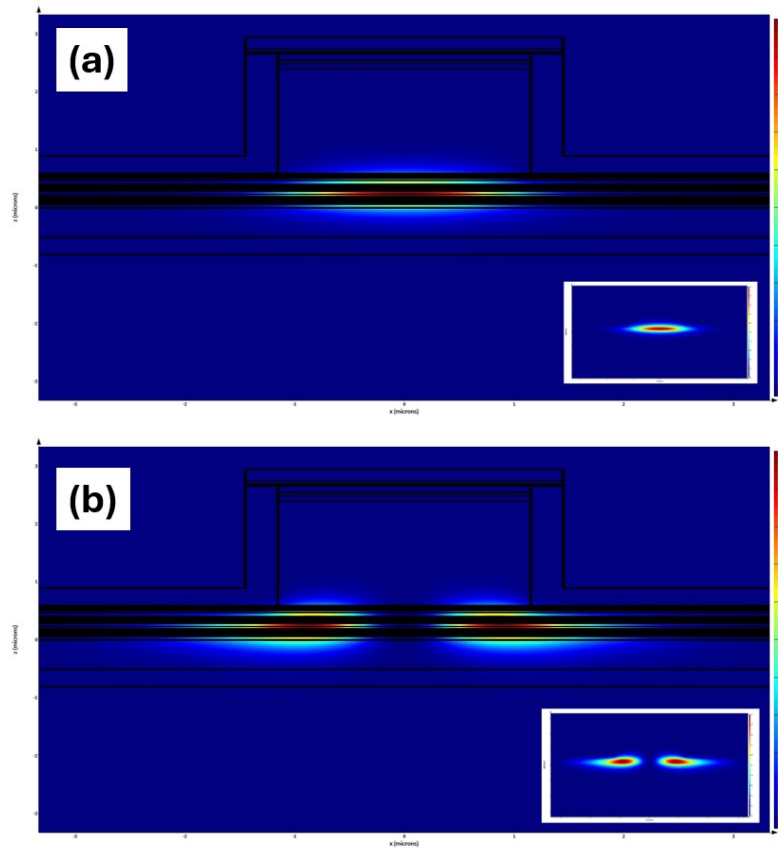


Figure 3.5 Simulated transverse optical field intensity distributions for a 2.3 μm ridge-width Fabry-Pérot laser obtained from optical cavity eigenmode analysis. (a) Fundamental lateral mode showing strong confinement within the ridge core region. (b) First higher-order lateral mode exhibiting a split intensity profile with a central node and increased radiation leakage.

To validate the accuracy of the optical cavity eigenmode analysis described in Section 3.2, a 2.3 μm ridge-width Fabry-Pérot laser structure was simulated. The detail cavity setting see

reference [135], [136], [137]. The calculated transverse optical field distributions for the two lowest-order lateral modes are shown in Fig. 3.5(a) and Fig. 3.5(b). The fundamental transverse mode exhibits strong confinement within the ridge region and a symmetric intensity profile centered at the waveguide core. In contrast, the first higher-order mode displays a split intensity distribution with two lateral maxima and a central node, characteristic of a higher-order lateral mode supported by a relatively wide ridge.

The extracted modal losses clearly distinguish the two modes. The fundamental mode exhibits a propagation loss of 3.73 dB/cm, whereas the first higher-order mode experiences a substantially larger loss of 78.06 dB/cm. This large difference in modal loss confirms that the higher-order mode is strongly suppressed by radiation leakage and reduced confinement outside the ridge region. The magnitude of this loss contrast is consistent with experimental observations in ridge-waveguide Fabry–Pérot lasers of similar geometry, where ridge widths near 2–3 μm typically support robust single-transverse-mode operation.

The strong discrimination between fundamental and higher-order modes demonstrates that the eigenmode solver accurately captures the refractive index profile, ridge confinement, and boundary conditions of the device structure. In particular, the correct prediction of high lateral-mode loss verifies that the implemented perfectly matched layer (PML) and radiation boundary treatments properly account for leakage into the surrounding cladding. This validation establishes confidence that the extracted confinement factors, modal losses, and Q-factors used in the travelling-wave time-domain simulations are physically reliable.

3.5.2 Validation of eight-band k.p model

The eight-band k.p model employed in this work is a well-established method for calculating the electronic structure of strained quantum nanostructures. It has been extensively validated in the literature for both Qdot and Qdash systems[108], [109], [138], [139], [140], particularly in InAs/InP and InAs/InGaAsP material platforms. The model self-consistently incorporates strain-

induced band mixing, valence-band coupling, and piezoelectric effects, making it suitable for accurately predicting transition energies, wavefunctions, and optical matrix elements in low-dimensional semiconductor structures. Given its broad acceptance and prior validation across numerous experimental studies, a separate standalone validation of the fundamental $k \cdot p$ formalism is not repeated here.

Instead, validation of the electronic-structure calculations in this dissertation is performed indirectly through case-by-case comparisons in the subsequent chapters. In Chapters 4 through 6, calculated transition energies, gain spectra, bandwidth enhancement trends, and differential gain improvements are consistently benchmarked against reported experimental data or physically reasonable device behavior. The agreement observed in these later analyses confirms that the implemented eight-band $k \cdot p$ model provides reliable electronic parameters for integration into the travelling-wave time-domain laser simulations.

3.5.3 Validation of TDTW model

The validity of the travelling-wave time-domain (TDTW) model was evaluated by comparing simulation results with experimental measurements of a single-section mode-locked Fabry–Pérot laser. The simulated temporal intensity profiles for both ascending and descending stacked configurations are shown in Fig. 3.11(a). In both cases, stable periodic pulse trains are observed, with a repetition period of 10.8 ps corresponding to a repetition frequency of approximately 92 GHz. This period is consistent with the cavity round-trip time determined by the device length, confirming that the time-domain solver correctly captures the longitudinal cavity dynamics. The inset of Fig. 3.11(a) shows the simulated pulse shapes on a femtosecond scale, yielding pulse widths of 164 fs and 135 fs for the two configurations, respectively, demonstrating the ability of the model to resolve ultrafast carrier–photon interactions.

Experimental autocorrelation measurements are shown in Fig. 3.11(b), where a pulse spacing of 10.81 ps is extracted [137]. The excellent agreement between simulated and measured repetition

periods verifies that the implemented boundary conditions and cavity feedback mechanisms in the TDTW framework accurately reproduce round-trip phase and gain conditions. Furthermore, the presence of clean, regularly spaced autocorrelation peaks indicates stable mode-locking operation, consistent with the simulated time-domain pulse train.

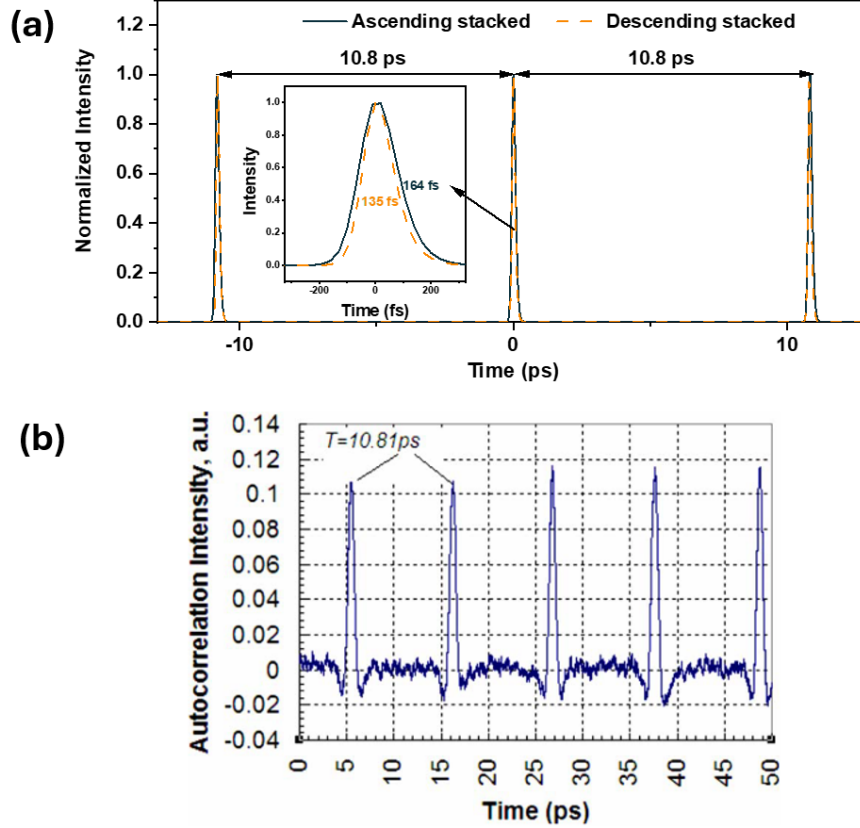


Figure 3.6 (a) Simulated time-domain pulse trains of a single-section mode-locked Fabry–Pérot laser for ascending and descending stacked active-region configurations. The repetition period is 10.8 ps, corresponding to a repetition frequency of approximately 92 GHz. The inset shows the simulated pulse shapes on a femtosecond timescale, with pulse widths of 164 fs and 135 fs for the two configurations. (b) Measured autocorrelation trace of the device, showing a pulse spacing of 10.81 ps [137], in excellent agreement with the simulated cavity round-trip time.

The optical spectrum measured from the descending stacked device is presented in Fig. 3.7, showing a well-defined frequency comb with uniform mode spacing of 92 GHz. This comb

spacing matches the repetition frequency obtained from both simulation and autocorrelation measurements, confirming self-consistency between time-domain and frequency-domain characteristics. The agreement in repetition rate, pulse stability, and comb spacing demonstrates that the TDTW model reliably captures the essential physics of mode-locked laser operation, including carrier dynamics, gain saturation, and cavity feedback. This validation establishes confidence in applying the model to the broadband and high-speed laser designs investigated in subsequent chapters.

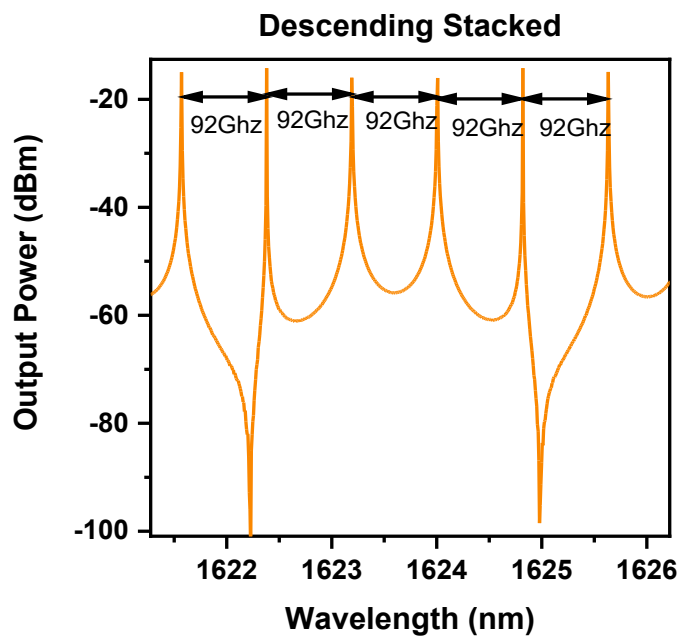


Figure 3.7 Simulated optical spectrum of the single-section mode-locked laser (descending stacked configuration), exhibiting a clear optical frequency comb with uniform mode spacing of 92 GHz.

Chapter 4 Broad Emission Bandwidth Using Chirped QDot Structures

4.1 Introduction

Semiconductor lasers based on self-assembled Qdot have attracted sustained interest for broadband optical applications, including semiconductor optical amplifiers, superluminescent diodes, and optical frequency comb sources. Compared with QW gain media, Qdot exhibit discrete energy states and inherent size dispersion, which naturally produce a broadened and relatively smooth gain spectrum. This intrinsic advantage has enabled Qdot devices to support wide optical bandwidths and improved temperature stability. However, as communication systems and comb-based photonic platforms continue to demand larger spectral coverage and flatter gain profiles, further gain engineering beyond natural inhomogeneous broadening has become necessary.

One effective approach to extending the gain bandwidth is the implementation of chirped stacked quantum-dot structures. In such configurations, multiple Qdot layers with intentionally varied heights are vertically arranged within the active region. Because the optical transition energy decreases with increasing dot height due to reduced quantum confinement, stacking layers of progressively different sizes creates a distributed transition energy spectrum across the active region. The ensemble response of these layers results in a broadened material gain profile. This strategy has been widely explored experimentally, particularly in InAs/InP systems operating around the 1.55 μm telecommunication window.

In many previously reported chirped Qdot devices, relatively thick spacer layers are introduced between adjacent dot layers to minimize interlayer interaction [141]. The purpose of such design is to ensure that each Qdot layer behaves independently, thereby preserving the intended transition energy distribution. While this decoupling strategy simplifies spectral design, it introduces several limitations from a device perspective. Thick spacer layers reduce vertical

carrier transport efficiency, increase the total thickness of the active region, and may shift the gain region away from the optical confinement center in ridge-waveguide structures, leading to reduced modal overlap and lower modal gain [25]. From a practical standpoint, reducing the spacer thickness would therefore be advantageous.

However, decreasing the spacer thickness inevitably introduces vertical coupling effects between Qdot layers. Two primary mechanisms contribute to this interaction: strain redistribution along the growth direction and electronic tunneling between adjacent dots. The accumulated strain field modifies the local band edges of individual layers, while tunneling coupling alters electron eigenstates through partial wavefunction delocalization. These effects can significantly perturb the optical transition energies that were originally engineered through height variation. In uniformly stacked Qdot structures, vertical coupling has been shown to produce bonding–antibonding splitting and spectral modification. In chirped structures, where transition energies differ from layer to layer, the situation becomes more complex and has not been systematically analyzed.

An additional and largely unexplored degree of freedom in chirped Qdot design is the stacking sequence itself. If the same set of Qdot heights is arranged in ascending order versus descending order, the spatial distribution of transition energies along the growth direction is reversed. Under finite vertical coupling, the strain redistribution and electronic interaction may affect these two sequences differently, potentially leading to distinct overall gain bandwidths. This suggests that stacking order is not merely a fabrication detail but a design parameter that may be exploited for bandwidth optimization.

In this chapter, the vertical coupling effects in four-layer chirped InAs/InP Qdot structures are investigated in detail. Both ascending and descending stacking configurations are examined. By combining electronic structure analysis with device-level simulations, the influence of strain coupling, tunneling interaction, and stacking sequence on optical transition distribution and gain bandwidth is clarified. The results reveal that vertical coupling, often regarded as detrimental, can instead be harnessed as a useful mechanism for broadband gain engineering.

4.2 Geometric Configuration of the Chirped QDot Structures

The geometric configurations investigated in this chapter are illustrated in Fig. 4.1. In order to clearly identify the influence of vertical coupling, three types of structures are considered: a single-layer reference structure and two four-layer chirped stacked structures with different stacking sequences.

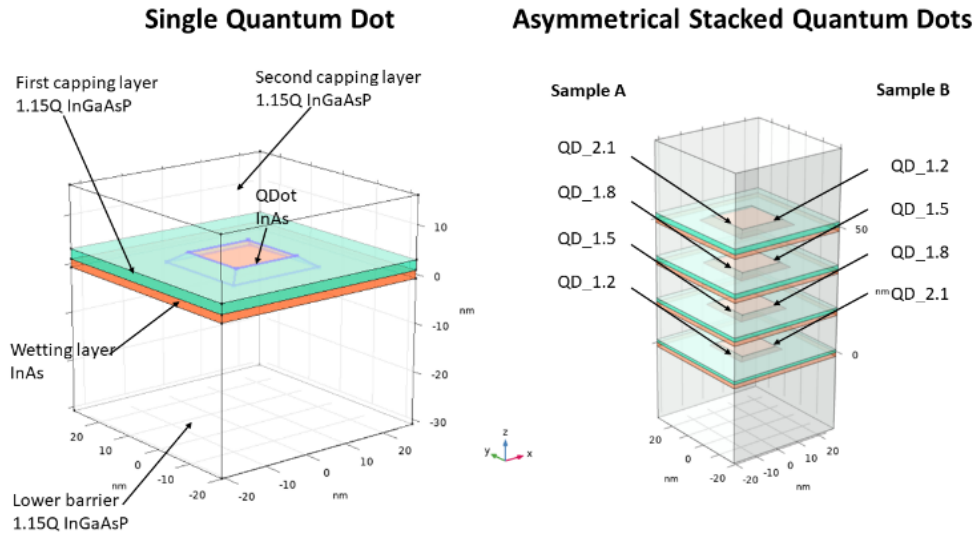


Figure 4.1 Geometric structures: single QDot structure (left), and two chirped stacked structures (right). The numbers in the right figure indicate the QDot heights in nm. The ascending and descending chirped QDot structure are indicated in the left and right side, respectively.

The single-layer structure serves as a baseline for evaluating interlayer interaction. It consists of a self-assembled InAs quantum dot embedded within an InGaAsP capping layer lattice matched to InP. The quantum dots formed by the double-capping growth process exhibit a truncated pyramid geometry, with the dot height primarily determined by the thickness of the first capping layer. In practical growth, the QDot height typically ranges from approximately 1.2 nm to 2.1 nm, and the base diameter increases with height due to strain-driven lateral expansion during self-assembly. In this study, the base diameter is varied from 27.5 nm to 35 nm in correspondence with

the selected heights. A wetting layer of thickness 1.1 nm is included beneath each QDot, consistent with experimentally reported InAs/InP systems. The lower barrier material is chosen to be identical to the surrounding capping layer in order to maintain lattice matching and simplify the interpretation of strain redistribution.

Building upon this reference structure, two chirped stacked configurations are constructed, each containing four QDot layers with different heights. The selected heights are 1.2 nm, 1.5 nm, 1.8 nm, and 2.1 nm. These values span the experimentally accessible range and produce sufficiently separated transition energies to generate a broad ensemble spectrum in the absence of coupling. The only distinction between the two stacked configurations lies in the ordering of these layers along the growth direction.

In the ascending stacked structure, the QDot height increases progressively from the bottom layer to the top layer. In the descending stacked structure, the ordering is reversed, such that the tallest QDot is positioned at the bottom and the smallest at the top. By keeping all other geometric parameters identical, including spacer thickness and material composition, any difference observed between these two configurations can be attributed solely to the stacking sequence under identical coupling conditions.

The total capping layer thickness between adjacent QDot layers, denoted as T_c , is varied from 10 nm to 30 nm. This parameter directly controls the strength of vertical coupling. When T_c is large, strain fields relax between layers and electronic wavefunctions remain largely confined within individual dots, approximating independent-layer behavior. As T_c decreases, strain accumulation and electronic tunneling become increasingly significant. By sweeping T_c , the transition from weak to strong coupling can be systematically examined.

This geometric setup allows isolation of three fundamental aspects: the intrinsic transition energy variation due to QDot height, the modification induced by vertical strain redistribution, and the additional perturbation caused by electronic tunneling. Most importantly, it enables evaluation of how the same coupling strength interacts differently with ascending and descending stacking

sequences. The following sections analyze these effects in detail, beginning with the strain redistribution in the stacked structures.

4.3 Optical Transition Energy of Isolated Quantum Dots

Before analyzing the stacked configurations, it is necessary to first examine the electronic structure of isolated quantum dots with different heights. This provides a reference for evaluating how vertical coupling modifies the intrinsic transition energies in the chirped structures. The strain distribution and band edge evolution along the growth direction for single-layer QDs are presented in Fig. 4.2.

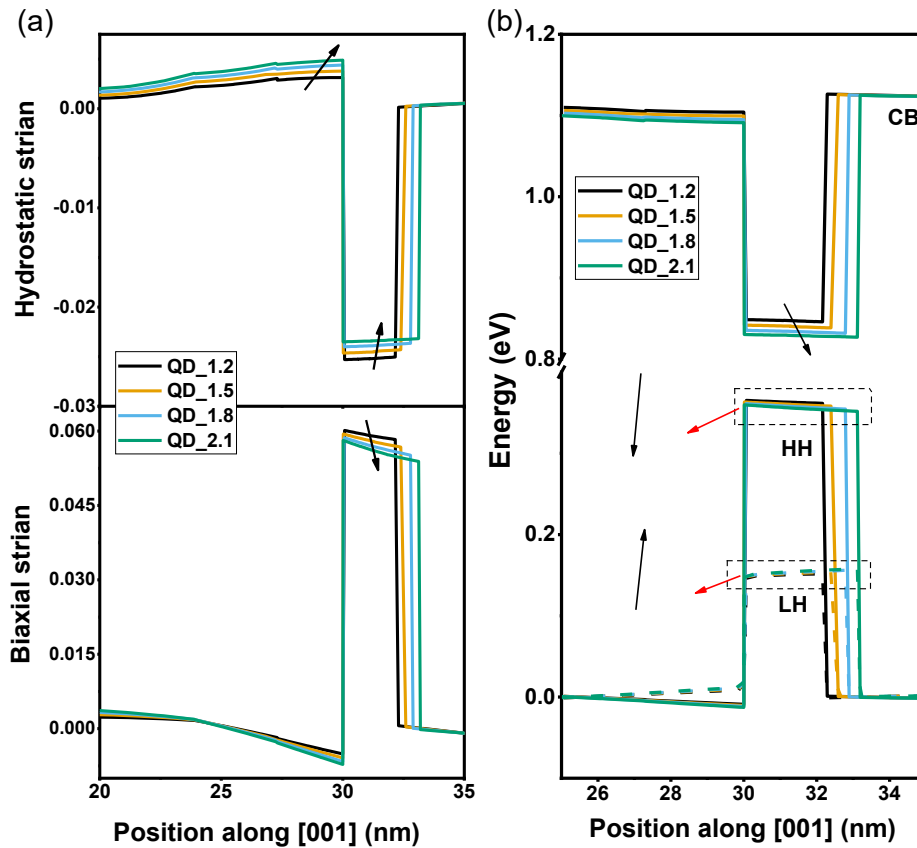


Figure 4.2 (a) The hydrostatic and biaxial strain distribution along vertical [001] direction; (b) the strained conduction band and valence band edges along [001] direction.

Figure 4.2(a) shows the hydrostatic and biaxial strain components along the vertical [001] direction for QDs with heights of 1.2 nm, 1.5 nm, 1.8 nm, and 2.1 nm. Within the wetting layer and QD region, the hydrostatic strain is compressive due to lattice mismatch between InAs and the InP-based surrounding material. In contrast, the lower barrier region experiences tensile strain, which partially compensates the compressive strain in the dot region. As the QD height increases, the strain distribution becomes more relaxed because the larger dot volume allows more effective redistribution of lattice mismatch. Consequently, both the hydrostatic and biaxial strain components decrease in magnitude with increasing height.

The corresponding conduction and valence band edge profiles are shown in Fig. 4.2(b). The reduction in hydrostatic strain leads to a downward shift of the conduction band edge and modifies the confinement potential experienced by electrons. Meanwhile, changes in biaxial strain influence the splitting between heavy-hole and light-hole states. For the truncated pyramid geometry considered here, the heavy-hole and light-hole separation remains sufficiently large, and the ground-state transition is dominated by heavy-hole character. Therefore, the primary contribution to the transition energy variation arises from the combined effects of reduced quantum confinement and modified hydrostatic strain.

The calculated ground-state optical transition energies as a function of QD height are presented in Fig. 4.3, together with reported experimental data. A monotonic decrease in transition energy with increasing QD height is observed. Larger QDs exhibit weaker confinement and slightly reduced strain-induced band modification, both of which contribute to a lower excitonic transition energy. The calculated results show excellent agreement with experimental measurements, with deviations within approximately 1.5%. This close agreement confirms that the electronic structure model accurately captures the combined effects of geometry and strain in the InAs/InP system.

These results establish two important conclusions. First, QD height provides an effective and predictable control parameter for tuning optical transition energy. Second, in the absence of vertical coupling, a chirped stacked structure composed of QDs with progressively varying heights should inherently exhibit a broadened ensemble transition spectrum. The following sections will demonstrate how this intrinsic distribution is modified when vertical strain accumulation and electronic tunneling coupling are introduced in closely spaced stacked configurations.

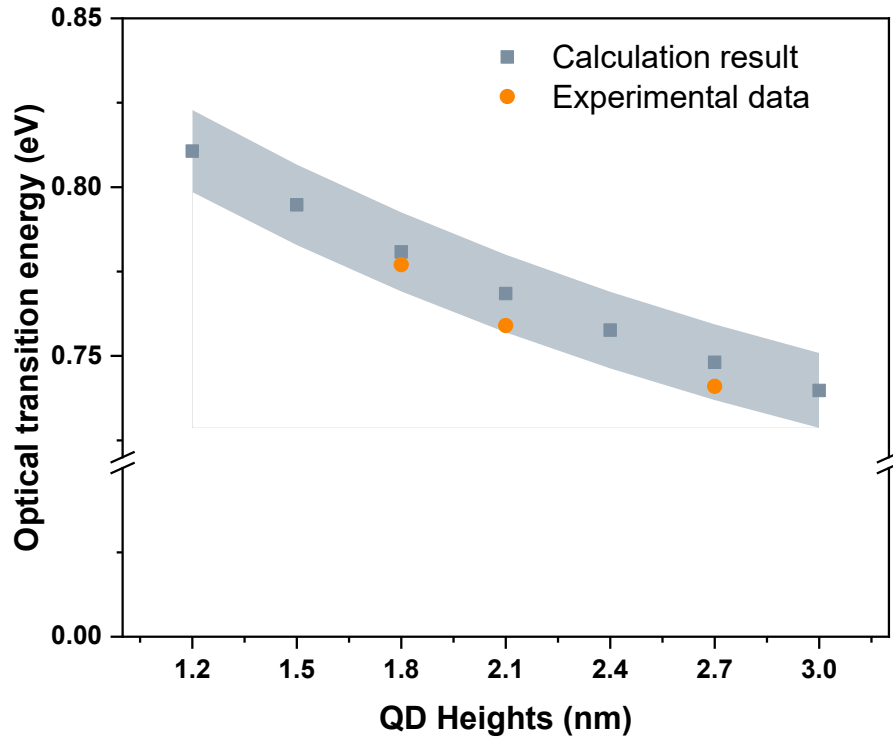


Figure 4.3 Comparison of optical transition energies between calculation results (with $\pm 1.5\%$ error) and experimental data in [142].

4.4 Vertical Strain Coupling in Chirped Stacked QDot

When multiple quantum-dot layers are vertically stacked with finite spacer thickness, the strain fields generated by each dot no longer remain confined locally. Instead, they interact and

accumulate along the growth direction. This strain redistribution constitutes the first and most fundamental component of vertical coupling in stacked QD structures. To evaluate its impact, the hydrostatic strain distribution along the [001] direction is calculated for both ascending and descending stacked configurations, and the results are shown in Fig. 4.4 and Fig. 4.5.

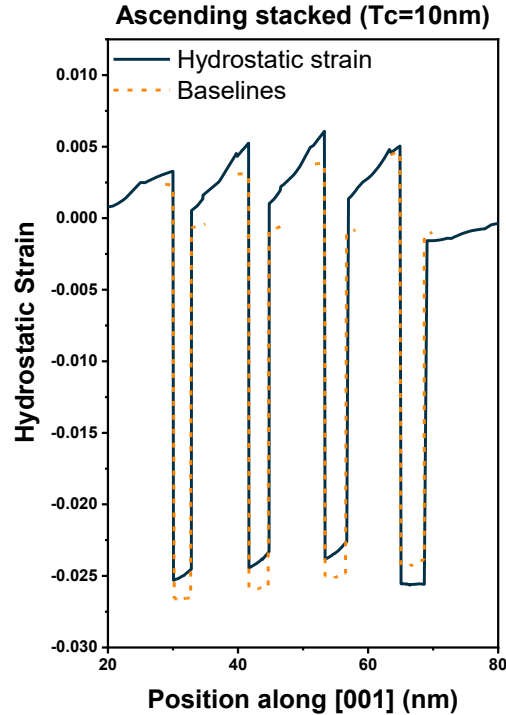


Figure 4.4 The hydrostatic strain distribution along vertical [001] direction for ascending stacked with $T_c=10$ nm.

For a relatively thin spacer thickness of $T_c = 10$ nm, pronounced strain redistribution is observed. Figure 4.4 presents the hydrostatic strain profile for the ascending stacked structure. Compared with the isolated reference case discussed in Section 4.3, the bottom three QD layers experience additional tensile compensation originating from the layers above them. Because the strain field generated by an upper dot extends downward through the spacer region, it partially

relaxes the compressive strain in the lower dots. As a result, the magnitude of hydrostatic strain in the bottom three layers is reduced relative to the isolated case. Since hydrostatic strain directly modifies the conduction band edge, this reduction leads to a downward shift of the conduction band in these layers.

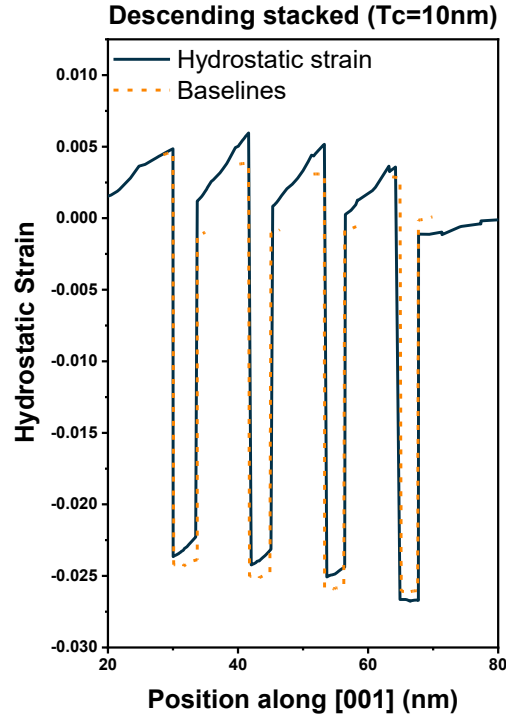


Figure 4.5 The hydrostatic strain distribution along vertical [001] direction for descending stacked with Tc=10 nm.

In contrast, the topmost QD behaves differently. The accumulated strain from the underlying layers propagates upward, and the top dot experiences enhanced compressive influence. Furthermore, it receives less tensile compensation from above because no additional QD layer is present. Consequently, the hydrostatic strain in the top layer increases relative to the isolated case, producing an upward shift of the conduction band edge. This asymmetric strain redistribution

between bottom and top layers is a characteristic feature of vertically stacked QD systems with thin spacers.

A similar trend is observed for the descending stacked configuration, as shown in Fig. 4.5. Although the stacking sequence differs, the general pattern of strain accumulation remains comparable: the bottom layers experience partial tensile compensation, while the top layer experiences enhanced compressive influence. This indicates that the magnitude and spatial distribution of strain coupling are primarily governed by spacer thickness rather than stacking order. The strain field is determined by mechanical boundary conditions and lattice mismatch, and thus depends mainly on interlayer separation.

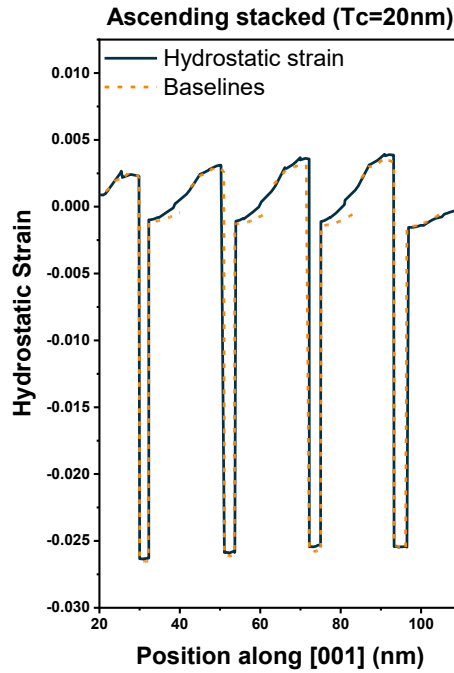


Figure 4.6 The hydrostatic strain distribution along vertical [001] direction for ascending stacked with $T_c=20$ nm.

When the spacer thickness increases to $T_c = 20\text{nm}$, as shown in Fig. 4.6, the strain profiles approach those of isolated dots. The additional tensile and compressive contributions from adjacent layers become negligible, and each QD layer behaves nearly independently. This demonstrates that vertical strain coupling can be effectively suppressed by increasing spacer thickness, consistent with the conventional decoupling strategy adopted in many experimental devices.

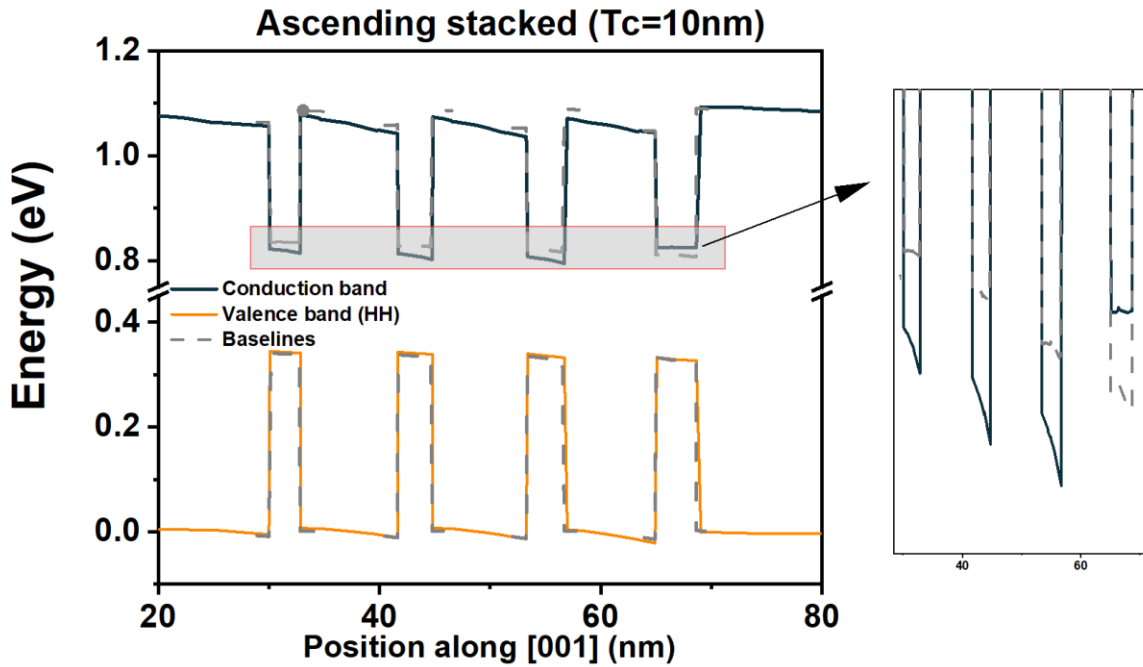


Figure 4.7 The strained conduction band and valence band edges along [001] direction for the ascending stacked with $T_c=10\text{ nm}$.

The corresponding conduction and valence band edge profiles for the ascending and descending structures with $T_c = 10\text{nm}$ are shown in Fig. 4.7 and Fig. 4.8. The conduction band edges of the bottom three layers shift downward, while that of the top layer shifts upward. The valence band edges exhibit comparatively minor variation, indicating that vertical strain coupling affects the conduction band more strongly in the present InAs/InP system. As a result, the primary

modification of optical transition energy arises from changes in electron confinement rather than hole states.

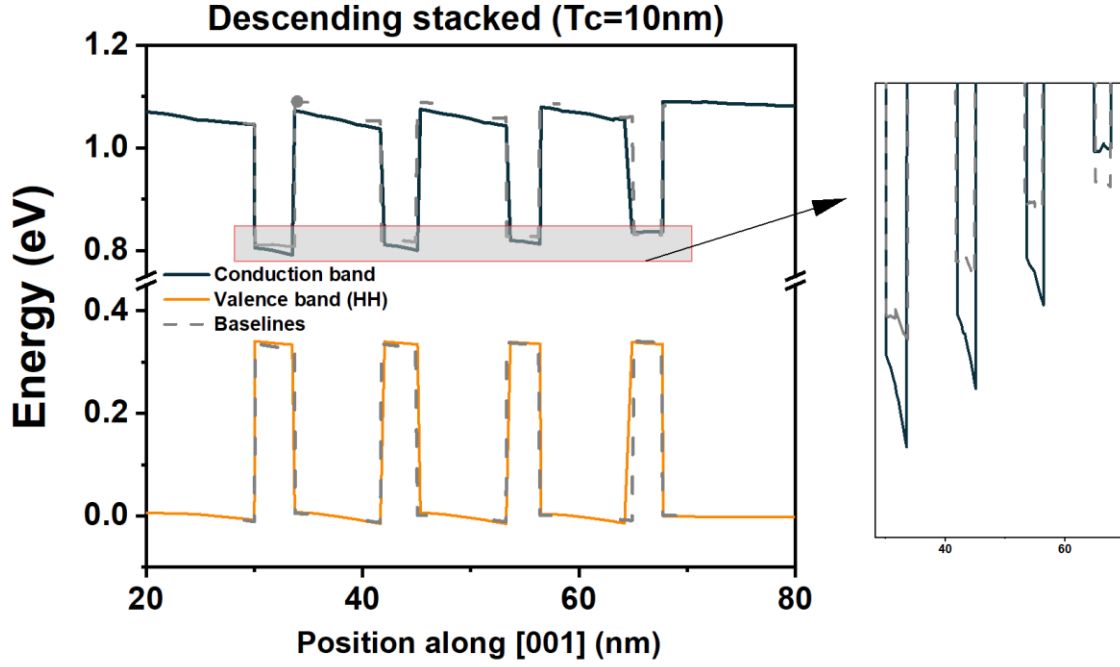


Figure 4.8 The strained conduction band and valence band edges along [001] direction for the descending stacked with Tc=10 nm.

These results confirm that vertical stacking introduces a non-uniform strain redistribution along the growth direction. Although the strain coupling strength is similar for ascending and descending configurations at a given spacer thickness, its effect on the overall transition energy distribution depends on how this redistribution interacts with the intrinsic height-dependent energy variation. This interplay between strain redistribution and stacking sequence will be analyzed in the following section.

4.5 Optical Transition Energy in Chirped Stacked QDot

While vertical strain redistribution modifies the band edges of individual layers, the optical transition energies of stacked structures are determined by the combined influence of strain and electronic coupling. To quantify this effect, the ground-state transition energies of each QD layer are calculated as a function of spacer thickness for both stacking sequences. The results are shown in Fig. 4.9 and Fig. 4.10.

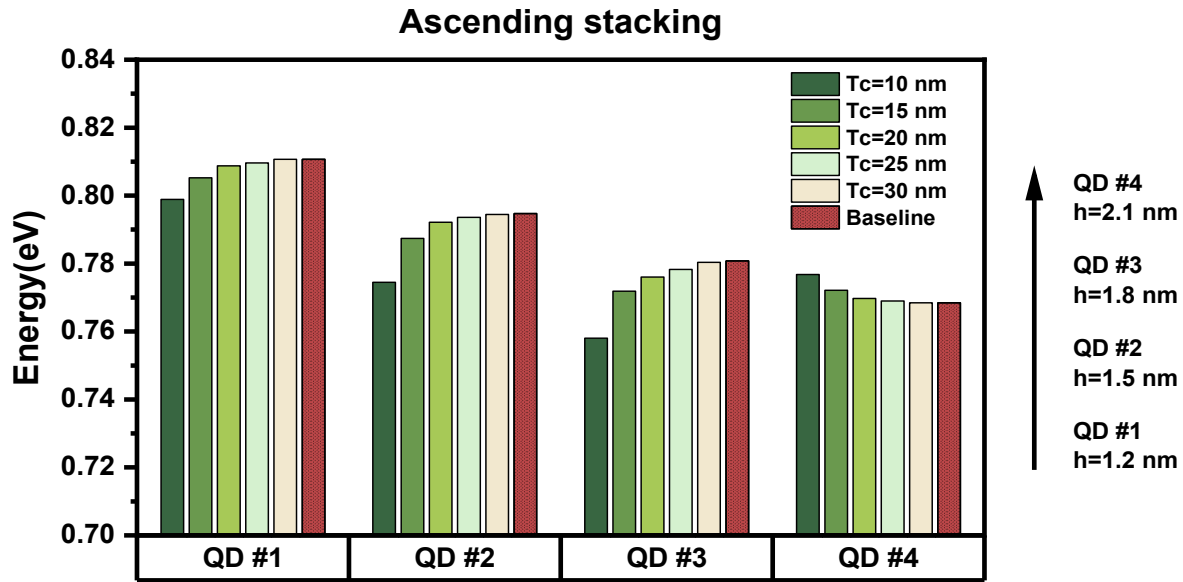


Figure 4.9 The evolution of optical transition energies as a function of capping layer thickness T_c for ascending stacked structure.

For a spacer thickness of $T_c = 10\text{nm}$, significant deviations from the isolated-dot reference energies are observed. In both stacking configurations, the transition energies of the bottom three layers decrease, while the transition energy of the top layer increases. This trend is consistent with the conduction band shifts discussed in Section 4.4. Because the electron states are more sensitive

to hydrostatic strain, the downward shift of the conduction band in the lower layers reduces their transition energies, whereas the upward shift in the top layer increases its transition energy.

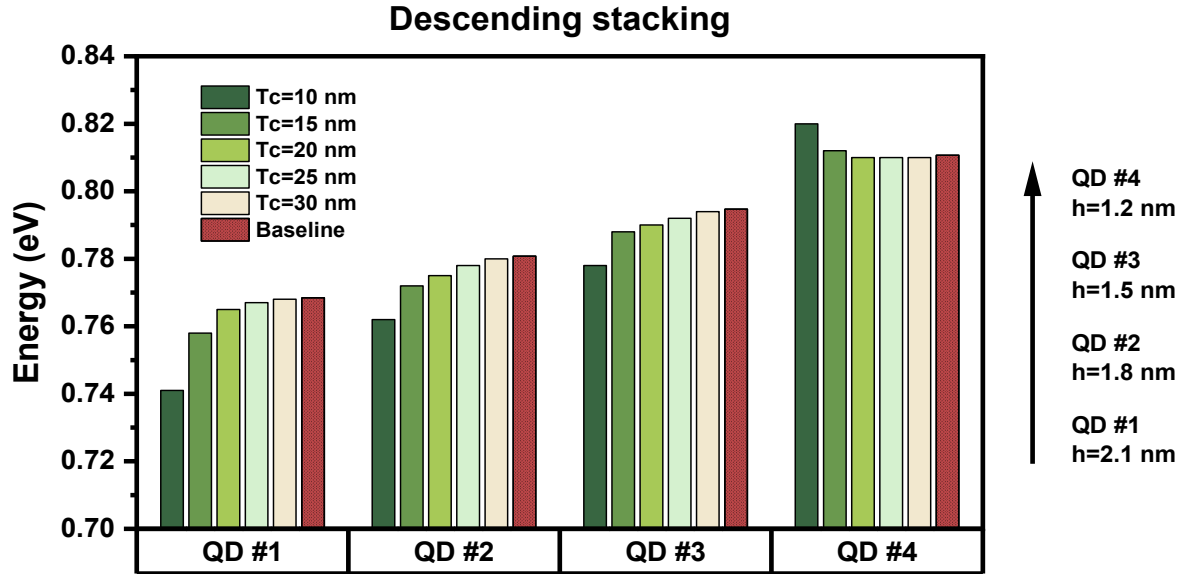


Figure 4.10 The evolution of optical transition energies as a function of capping layer thickness T_c for descending stacked structure.

Although the qualitative redistribution is similar for both stacking sequences, its effect on the global energy spread differs substantially. In the ascending stacked structure, where the intrinsic transition energy decreases from bottom to top, the strain-induced downward shift of lower-layer energies and upward shift of the top-layer energy effectively compress the overall transition energy distribution. The lowest-energy and highest-energy states move closer together, resulting in a reduced energy span across the four layers.

In contrast, in the descending stacked structure, the intrinsic energy ordering is reversed. The lowest intrinsic transition energy belongs to the bottom layer, and the highest to the top layer. Under vertical strain coupling, the bottom layer shifts further downward and the top layer shifts further upward. Consequently, the total energy separation between the lowest and highest

transition energies increases. In this case, the same strain redistribution mechanism enhances rather than compresses the transition energy spread.

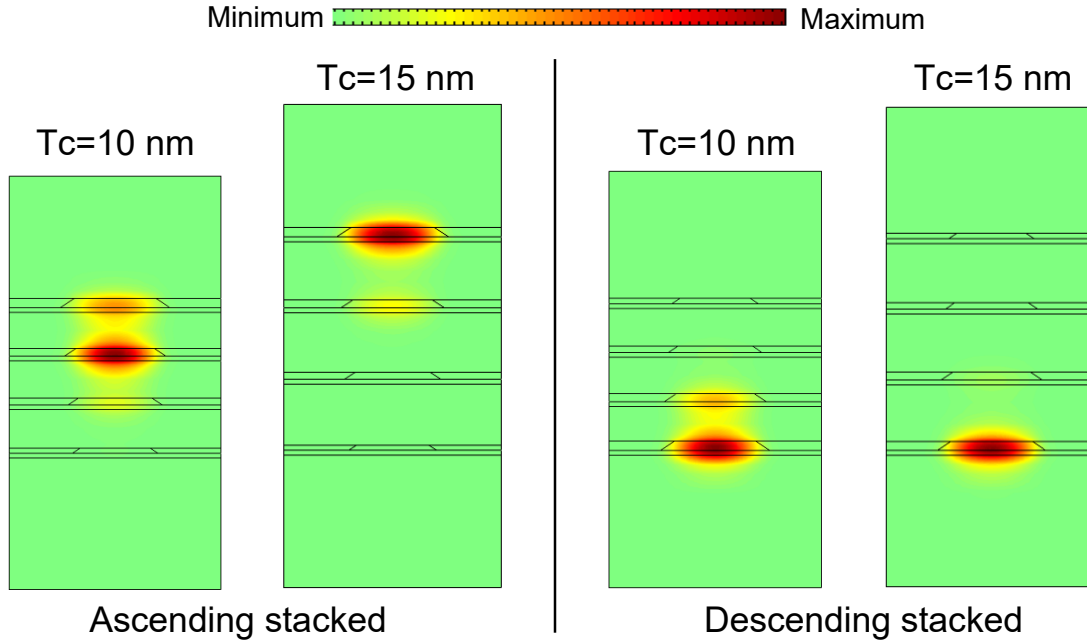


Figure 4.11 The probability density of lowest electron eigenstate for ascending and descending stacked structure at capping layer thickness of 10 and 15 nm, respectively.

In addition to strain effects, electronic coupling contributes to the modification of eigenstates when spacer thickness is sufficiently small. Because electrons possess relatively small effective mass in the InAs/InP system, their envelope wavefunctions extend beyond individual QD boundaries and partially overlap with adjacent layers. The calculated probability density distributions of the lowest electron eigenstate are shown in Fig. 4.11. For $T_c = 10\text{nm}$, partial delocalization across neighboring layers is observed in both stacking sequences. As the spacer thickness increases, the wavefunctions become progressively confined within individual QDs, indicating suppression of tunneling interaction.

It is important to note that in chirped structures the energy mismatch between adjacent layers prevents strong resonant coupling, and therefore no pronounced bonding–antibonding splitting is observed. Nevertheless, weak tunneling contributes to slight adjustments of electron confinement energies and enhances the sensitivity of the lowest states to strain-induced band shifts. The combined action of strain redistribution and weak electronic delocalization ultimately determines the transition energy evolution in the stacked structures.

The most significant conclusion is that stacking sequence acts as an effective design parameter for gain bandwidth engineering. Under finite vertical coupling, ascending stacking reduces the intrinsic energy spread, while descending stacking amplifies it. This distinction does not arise from differences in coupling strength, which is primarily controlled by spacer thickness, but from the interaction between coupling-induced band shifts and the intrinsic height-dependent energy ordering. Therefore, stacking order directly influences the achievable ensemble transition energy distribution and, consequently, the material gain bandwidth.

4.6 Performance of Single Section Mode-Lock Laser

The transition energy redistribution discussed in the previous section directly modifies the ensemble gain spectrum of the chirped quantum-dot structures. To evaluate this effect at the device level, both ascending and descending stacked configurations are incorporated into a single-section Fabry–Perot mode-locked laser model using the travelling-wave time-domain framework described in Chapter 3. The simulated device has a cavity length of 456 μm and a ridge width of 2.5 μm , with facet reflectivities of 99% and 33%. The active region consists of 31 QD groups with an inhomogeneous broadening of 30 meV.

The calculated material gain spectra at an injection current density of 880 A/cm² are shown in Fig. 4.12. A clear difference between the two stacking sequences is observed. The ascending stacked structure exhibits a full width at half maximum (FWHM) of approximately 137 nm, while

the descending stacked structure achieves a significantly broader FWHM of 174 nm. This corresponds to an enhancement of roughly 27% in gain bandwidth for the descending configuration. In addition to the increased bandwidth, the gain profile of the descending structure is more uniform across the spectral range, indicating improved spectral flatness.

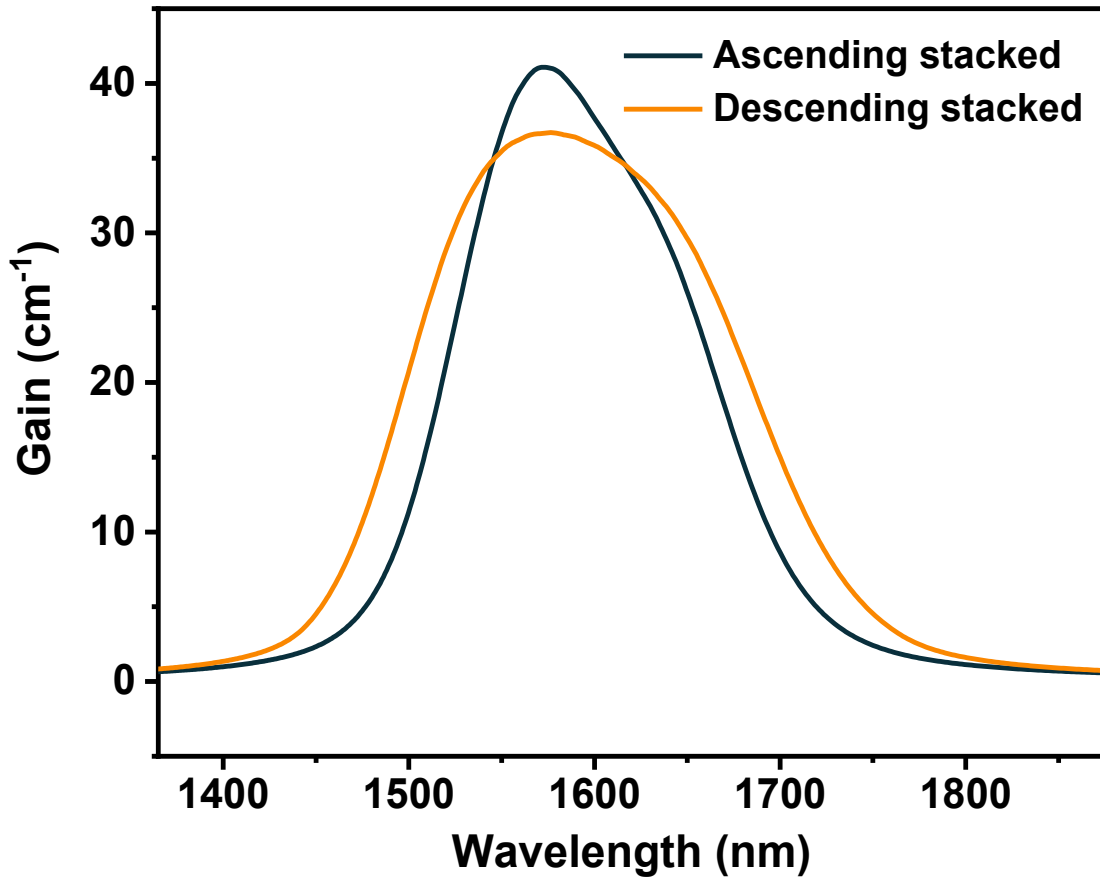


Figure 4.12 Laser performance under RT at injection current density of 880 A/cm²: (a) the gain spectrum of ascending and descending structures.

The corresponding optical spectra generated by the mode-locked laser are presented in Fig. 4.13(a) and Fig. 4.13(b). Both structures support stable optical frequency comb operation with a mode spacing of 92 GHz, determined by the cavity length. However, the descending stacked

structure produces a noticeably broader optical spectrum. The -3 dB bandwidth of the optical comb is larger, and more longitudinal modes are sustained above the threshold level. This behavior is consistent with the broader material gain profile discussed above.

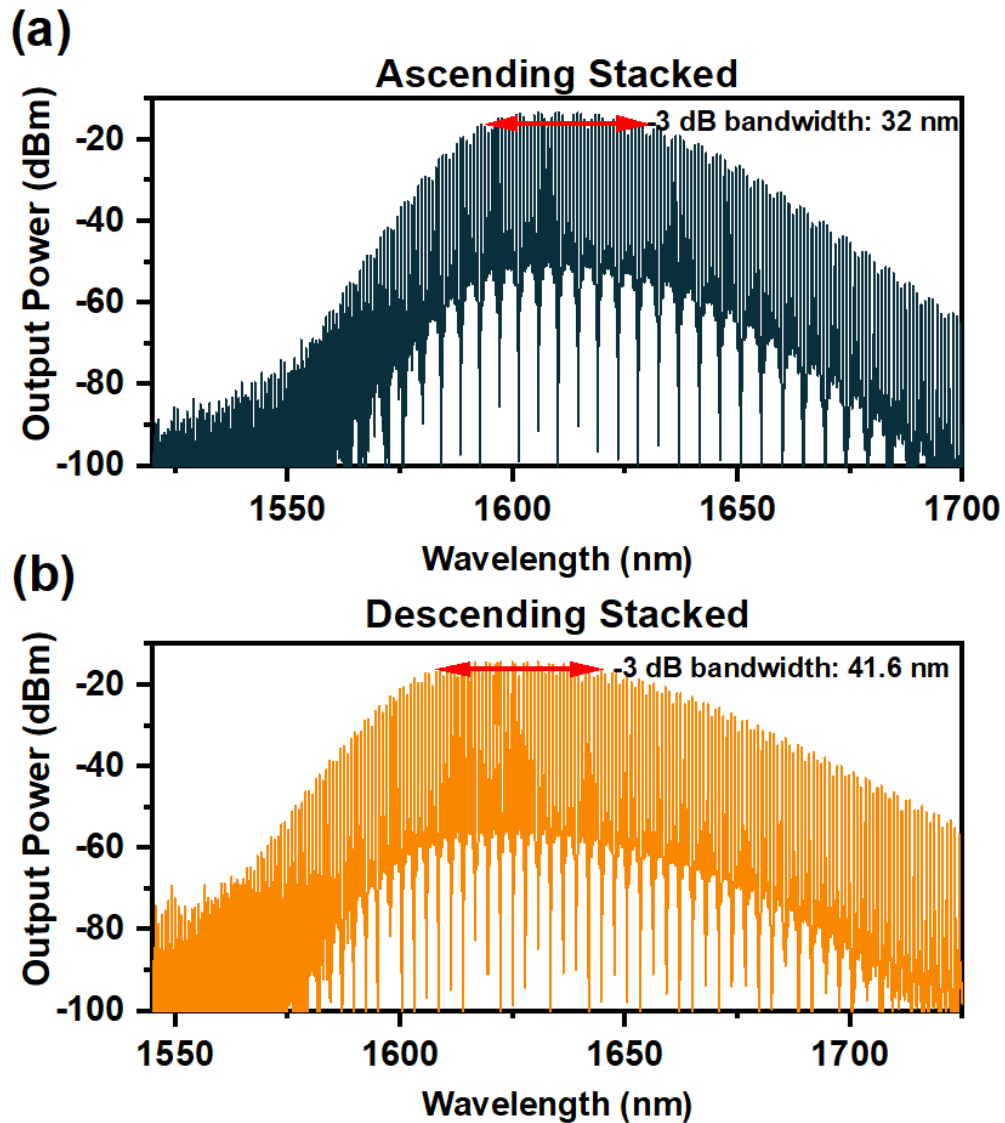


Figure 4.13 Laser performance under RT at injection current density of 880 A/cm²: (a) the optical spectrum for ascending stacked structure; and (b) the optical spectrum for descending stacked structure.

The dependence of optical bandwidth on injection current density is shown in Fig. 4.14(a). At moderate injection levels, both structures exhibit increasing bandwidth as carrier density rises and gain saturation flattens the spectrum. At higher injection levels, however, the difference between the two configurations becomes more pronounced. The ascending stacked structure shows a tendency toward bandwidth reduction due to enhanced mode competition and spectral narrowing, whereas the descending stacked structure maintains a relatively wide -3 dB bandwidth over a broader current range. Figure 4.14(b) further illustrates that the descending configuration supports a larger number of comb lines within the -3 dB envelope, particularly at high injection levels.

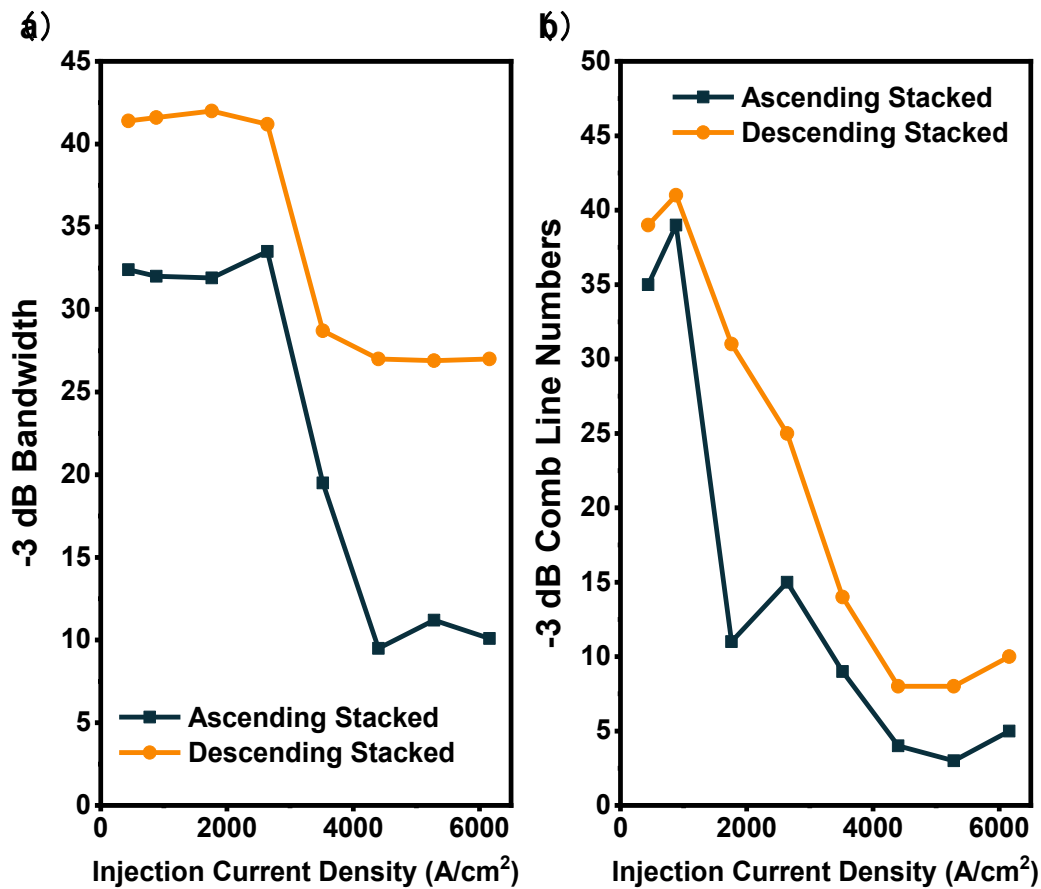


Figure 4.14 (a) Optical spectrum -3 -dB bandwidth as a function of injection current density; and (b) the number of -3 -dB comb lines as a function of injection current density.

These results demonstrate that the stacking sequence influences not only the static gain bandwidth but also the dynamic stability of mode-locked operation. A broader and flatter gain spectrum reduces intracavity mode competition and enables more uniform amplification of longitudinal modes, thereby enhancing comb stability and spectral coverage. Importantly, the improvement observed in the descending structure does not require modification of QD height values or material composition. Instead, it arises solely from reordering the same set of QD layers under finite vertical coupling conditions.

The findings of this chapter reveal that vertical coupling, traditionally minimized through thick spacer layers, can be harnessed as a useful design tool. By carefully selecting spacer thickness and stacking sequence, the intrinsic transition energy distribution of chirped QD structures can be engineered to enhance gain bandwidth and improve comb performance. This provides a practical and physically intuitive strategy for broadband QD laser design.

4.7 Extension to Chirp Stacked QDash

The vertical strain coupling mechanism identified in the preceding sections is not limited to quantum-dot geometries. To further examine the generality of this effect, a similar study was conducted on chirped stacked InAs/InGaAsP quantum-dash (Qdash) structures.

Quantum dashes, owing to their elongated lateral geometry and reduced confinement in one in-plane direction, exhibit different density-of-states characteristics compared with quantum dots. Nevertheless, their electronic structure remains highly sensitive to strain redistribution along the growth direction. This makes them an ideal platform for verifying whether stacking sequence can similarly influence gain bandwidth through vertical coupling.

In the Qdash study, two single-section Fabry–Perot mode-locked laser structures were designed, each consisting of five Qdash layers with different heights ranging from 1.2 nm to 2.4

nm. As in the QD case, ascending and descending stacking sequences were considered while keeping all other geometric and material parameters identical. The bright exciton transition energies of the target Qdash layers were calculated using the same 8-band $k\cdot p$ model incorporating strain and piezoelectric effects. The resulting exciton energies for ascending and descending configurations are shown in Fig. 4.15(a) and Fig. 4.15(b), respectively, while the corresponding hydrostatic strain profile is presented in Fig. 4.15(c).

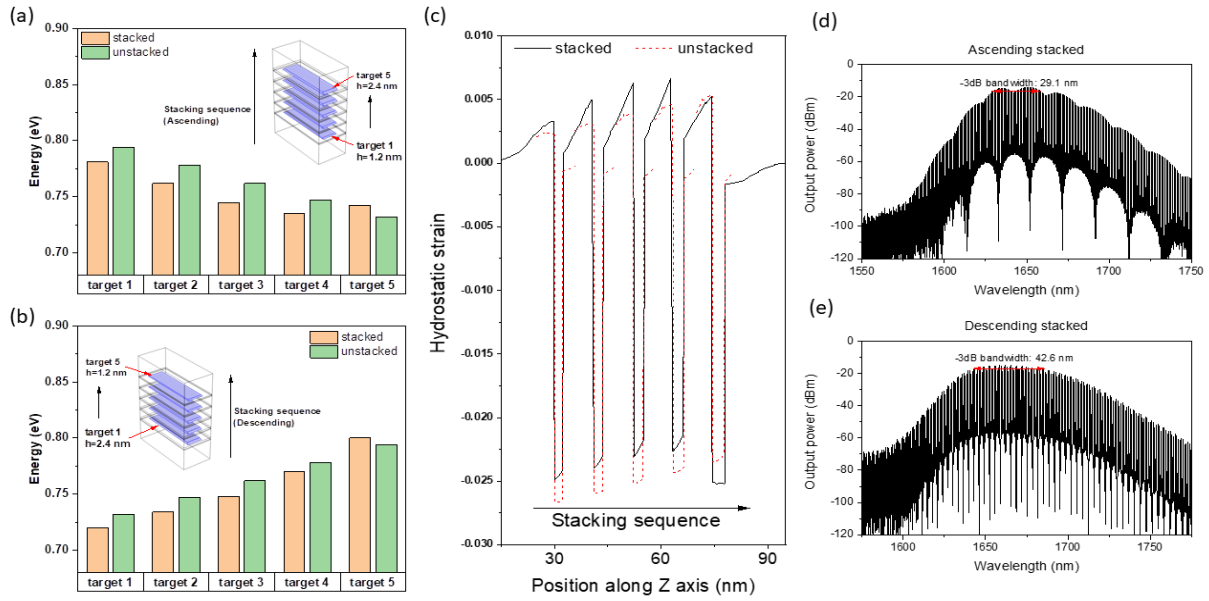


Figure 4.15 The bright exciton energy of target Qdash in ascending stacked structure; (b) in descending stacked structure; (c) the hydrostatic strain profile; (d) and (e) the optical spectrums.

The results reveal a redistribution pattern closely analogous to that observed in QD structures. For both stacking sequences, the exciton energies of the lower and middle layers decrease relative to their isolated reference values, whereas the topmost layer exhibits an increased transition energy. The hydrostatic strain profile confirms that lower layers experience partial tensile compensation, while residual strain accumulates toward the top layer. The reduction of hydrostatic strain lowers the conduction band edge and reduces exciton energy, whereas increased compressive strain raises

it. As in the QD case, the magnitude of strain redistribution is largely determined by spacer thickness rather than stacking order.

However, the global impact on energy distribution depends critically on the stacking sequence. In the ascending configuration, vertical strain coupling compresses the energy spacing between layers, leading to a narrower ensemble transition distribution. In contrast, the descending configuration amplifies the separation between the lowest and highest transition energies, resulting in a broader intrinsic gain bandwidth. This behavior confirms that the stacking-order-dependent redistribution mechanism is not specific to QDs but is a general consequence of vertical strain coupling in chirped nanostructure stacks.

The device-level implications were evaluated using the travelling-wave time-domain model for single-section mode-locked lasers. The simulated optical spectra are shown in Fig. 4.15(d) and Fig. 4.15(e). The -3 dB output bandwidth of the ascending stacked Qdash structure is approximately 29.1 nm, whereas the descending stacked configuration achieves a significantly larger bandwidth of 42.6 nm. This substantial improvement is obtained without increasing the number of stacking layers or modifying the dash height range. Instead, it results solely from reordering the same set of layers under finite vertical coupling conditions.

The consistency between QD and Qdash systems demonstrates that vertical strain coupling is a universal design mechanism in chirped stacked nanostructures. Rather than being an undesirable artifact that must be suppressed by thick spacers, it can be strategically exploited to enhance gain bandwidth. By appropriately selecting stacking sequence and spacer thickness, broadband performance can be achieved without increasing structural complexity. This general principle provides a flexible pathway for engineering next-generation broadband semiconductor lasers.

4.8 Conclusions

In this chapter, the vertical coupling effects in chirped stacked quantum-dot and quantum-dash structures have been systematically investigated. Starting from isolated nanostructures, the intrinsic dependence of optical transition energy on dot or dash height was established and validated against experimental data. Building upon this baseline, vertically stacked chirped configurations with varying spacer thickness were analyzed to clarify the role of strain redistribution and electronic tunneling coupling.

It was shown that when spacer thickness is reduced, vertical strain fields overlap and accumulate along the growth direction. The bottom layers experience partial tensile compensation, leading to reduced hydrostatic strain and downward shifts of conduction band edges, while the topmost layer experiences enhanced compressive influence and an upward shift in transition energy. Although the magnitude of strain coupling is primarily governed by spacer thickness and is similar for different stacking sequences, its impact on the overall transition energy distribution depends critically on the intrinsic ordering of layer energies.

A key finding of this work is that stacking sequence acts as an effective design parameter for gain bandwidth engineering. In ascending chirped structures, vertical coupling compresses the transition energy spread and reduces gain bandwidth. In descending chirped structures, the same coupling mechanism amplifies the energy separation between layers, resulting in a broader ensemble gain spectrum. Device-level simulations of single-section mode-locked lasers confirmed that descending stacked structures achieve significantly larger optical bandwidth and improved comb stability without increasing the number of active layers.

Importantly, this mechanism was demonstrated to be general across both quantum-dot and quantum-dash systems. The consistent behavior observed in QD and Qdash structures indicates that vertical strain coupling is not merely a material-specific phenomenon but a universal feature

of chirped stacked nanostructures. Rather than suppressing vertical interaction through thick spacers, controlled coupling can be intentionally exploited to enhance broadband performance.

The results presented in this chapter establish vertical coupling as a practical and physically intuitive tool for gain spectrum engineering. In the following chapters, this understanding will be extended to explore additional coupling mechanisms and their implications for threshold reduction, differential gain enhancement, and high-speed modulation in advanced semiconductor laser architectures.

Chapter 5 Threshold Reduction from Lateral Coupling

Effects in InAs/InGaAsP Qdash Structures

5.1 Introduction

Quantum-dot and quantum-dash nanostructures have become important gain media for next-generation optoelectronic devices owing to their discrete energy states, reduced temperature sensitivity, and low threshold current operation. While quantum dots are often treated as ideal zero-dimensional systems, quantum dashes represent a quasi-zero-dimensional structure formed through anisotropic elongation during Stranski–Krastanov growth on InP substrates. In the InAs/InGaAsP material system, the relatively small lattice mismatch promotes elongation along the $[1\bar{1}0]$ direction, producing wire-like nanostructures commonly referred to as quantum dashes.

Compared with quantum dots, quantum dashes possess significantly larger lateral dimensions and are typically more densely distributed on the growth plane. Their elongated geometry increases the effective gain volume and modifies the density of states, which is advantageous for high-power and broadband applications. However, this morphology also raises an important question that is often neglected in conventional modeling: are adjacent Qdashes truly electronically isolated?

Most theoretical treatments of Qdash systems assume isolated nanostructures and focus primarily on vertical stacking effects. Lateral coupling between neighboring Qdashes is generally ignored, based on the assumption that carrier wavefunctions remain confined within individual dashes. While this approximation is reasonable for sparsely distributed quantum dots, it may not hold for InAs/InGaAsP Qdash systems, where the average spacing between adjacent dashes can be only a few nanometers and the conduction band offset is relatively small.

Lateral interdash coupling can introduce additional carrier transport channels through tunneling. Such tunneling may degrade carrier confinement by enabling escape pathways, but it

can also enhance carrier redistribution efficiency by transferring carriers from high-energy to low-energy nanostructures. The net impact of lateral coupling on laser performance is therefore not trivial. In large-volume devices, improved carrier redistribution may reduce threshold current, whereas in small-volume cavities, additional carrier leakage or non-radiative recombination could offset potential benefits.

Experimental observations using time-resolved photoluminescence have suggested the existence of lateral coupling in dense Qdash ensembles, yet systematic theoretical investigation of this phenomenon in InAs/InGaAsP systems remains limited. In particular, the dependence of coupling strength on morphological parameters such as Qdash height, width, and lateral spacing has not been fully quantified, nor has its influence on device-level performance been rigorously evaluated.

In this chapter, lateral coupling in InAs/InGaAsP Qdash structures is investigated from the microscopic electronic-structure level to the device-performance level. A parallel Qdash pair model is constructed to analyze tunneling mechanisms between adjacent nanostructures. The resulting tunneling rates are incorporated into the travelling-wave time-domain laser model developed in Chapter 3. This multiscale approach allows direct evaluation of how morphological control of Qdash ensembles influences carrier redistribution and laser threshold behavior.

5.2 Geometry and Morphological Characteristics of InAs/InGaAsP Quantum Dashes

The lateral coupling strength between adjacent quantum dashes is fundamentally governed by their geometry and spatial distribution. Unlike idealized quantum dots with nearly symmetric confinement, self-assembled InAs/InGaAsP Qdashes exhibit pronounced anisotropy and significant morphological variation. To construct realistic simulation structures, statistical analysis

of scanning electron microscopy (SEM) and atomic force microscopy (AFM) data was performed, and the extracted morphological distributions are summarized in Fig. 5.1.

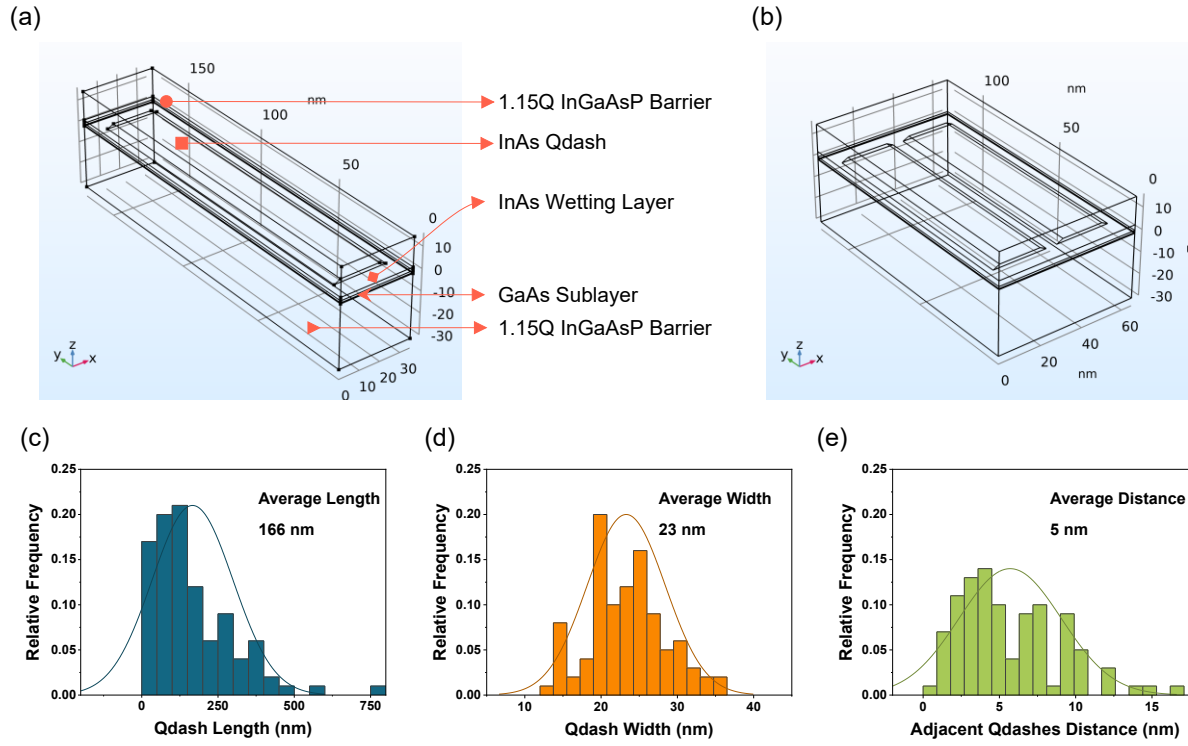


Figure 5.1 Geometric structure: (a) isolated single quantum dash, (b) quantum dash pair. Quantum dash morphology statistical data: (c) length distribution, (d) width distribution, (e) adjacent Qdash distance.

Figure 5.1(a) illustrates the three-dimensional geometry adopted for an isolated Qdash. The dash is modeled as a flat-topped prism embedded within a 1.15Q InGaAsP barrier lattice-matched to InP. A thin GaAs sublayer and an InAs wetting layer are included beneath the Qdash to reflect typical experimental growth conditions. The flat-top geometry is selected based on post-growth SEM observations, which show that although double-capping techniques reduce peak-height variation, the resulting Qdashes still retain a trapezoidal cross-section rather than a perfectly symmetric dome.

The statistical distributions of Qdash dimensions are shown in Fig. 5.1(c)–5.1(e). The dash length ranges from approximately 40 nm to 300 nm, with an average value near 166 nm. The width varies from 15 nm to 40 nm, with an average around 23 nm. In contrast to length and width, the height exhibits a relatively narrow but highly influential distribution, typically between 1.1 nm and 1.9 nm after capping. Importantly, AFM studies reveal that Qdash height often presents a dual-scale distribution consisting of plateau and peak features, which contributes significantly to inhomogeneous broadening.

The lateral spacing between adjacent Qdashes along the direction perpendicular to elongation is particularly critical for evaluating interdash coupling. As shown in Fig. 5.1(e), the edge-to-edge distance ranges from nearly touching (0 nm) up to approximately 15 nm, with an average spacing of about 5 nm. Such close proximity implies that electron wavefunctions, especially in the presence of relatively small conduction band offsets, may extend beyond individual Qdash boundaries and overlap with neighboring structures.

Two important observations arise from these morphological characteristics. First, although Qdash length can vary widely, the optical transition energy is primarily sensitive to height and width rather than length. Second, the combination of relatively large lateral dimensions and small average spacing creates conditions under which lateral tunneling may become significant, particularly for electron states. Therefore, realistic modeling of Qdash-based devices must account for the possibility of interdash electronic interaction rather than assuming complete isolation.

Based on these statistical observations, a representative Qdash pair structure is constructed, as illustrated in Fig. 5.1(b). In this configuration, two adjacent Qdashes are placed parallel to each other along the elongation direction, and their relative height, width, and separation are varied systematically. This model enables quantitative evaluation of how morphological variations influence wavefunction overlap and tunneling probability, which will be analyzed in the following sections.

5.3 Electronic Structure of Isolated Quantum Dashes

Before introducing lateral coupling effects, it is essential to first understand the electronic structure and optical properties of an isolated InAs/InGaAsP quantum dash. Due to the pronounced anisotropic geometry of Qdashes, their confinement characteristics differ substantially from those of nearly symmetric quantum dots. The elongated lateral dimension introduces quasi-one-dimensional features into an otherwise zero-dimensional system, leading to distinctive energy level structures and density-of-states distributions.

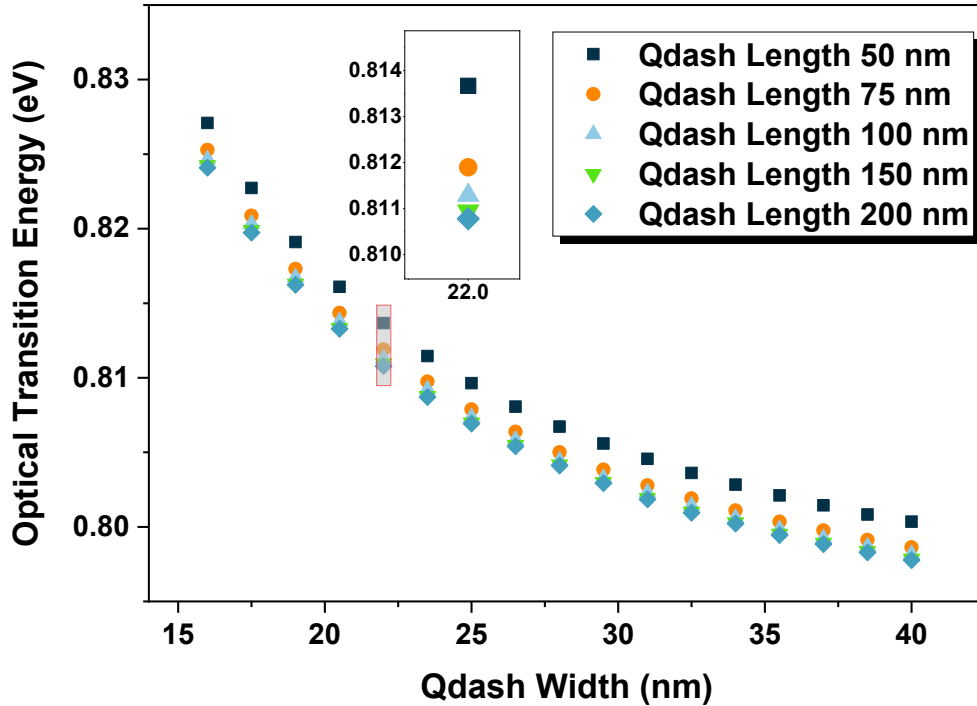


Figure 5.2 The change of Qdash ground state optical transition energy as function of Qdash width and length.

Figure 5.2 shows the dependence of the ground-state optical transition energy on Qdash width and length. Increasing the width from 15 nm to 40 nm results in a noticeable reduction in transition

energy of approximately 20 meV. This behavior arises from weakened lateral confinement along the width direction. In contrast, variation of Qdash length produces only a minor shift in transition energy. Increasing the length from 50 nm to 200 nm reduces the transition energy by only a few meV, and beyond 100 nm the influence becomes almost negligible. This weak sensitivity can be attributed to the already weak confinement along the elongation direction, where the effective confinement length is much larger than the carrier wavelength.

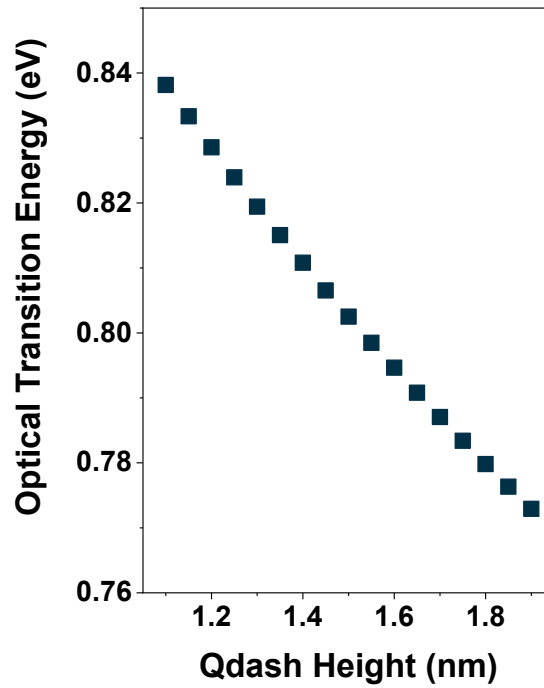


Figure 5.3 The change of Qdash ground state optical transition energy as function of Qdash height.

The Qdash height, however, plays a dominant role in determining the optical transition energy. As shown in Fig. 5.3, increasing the height from 1.1 nm to 1.9 nm leads to a nearly linear decrease of approximately 65 meV in transition energy. This strong dependence originates from the vertical quantum confinement and the associated strain modification of the conduction and valence band

edges. Even small fluctuations in height can therefore produce significant variations in emission energy. Although double-capping techniques help reduce height non-uniformity, residual variations remain a major source of inhomogeneous broadening in Qdash ensembles.

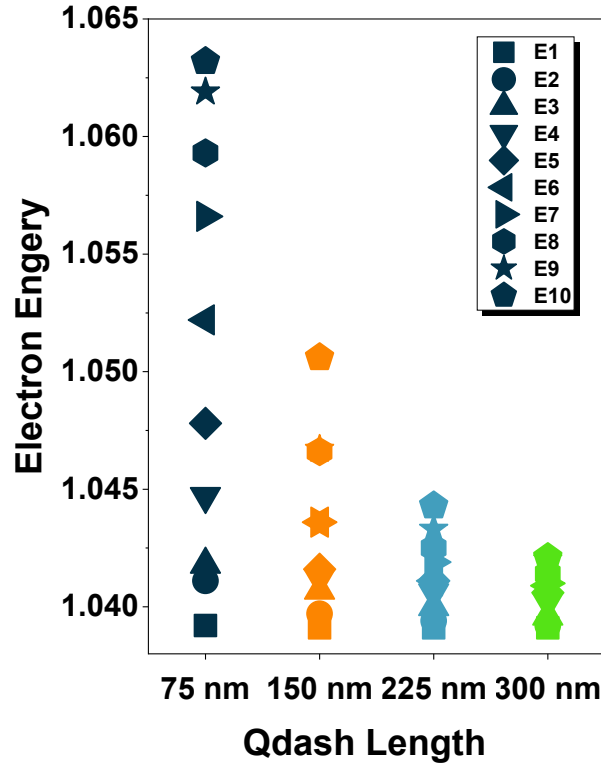


Figure 5.4 First 10 electron eigen states energy distribution change with Qdash length.

While Qdash length has minimal impact on ground-state transition energy, it strongly influences the electronic eigenstate distribution. Figure 5.4 presents the evolution of the first several electron energy levels as a function of dash length. As the length increases, the spacing between adjacent energy levels decreases, and the number of confined states within a given energy range increases. This leads to the formation of a mini-band ladder structure between the ground-state S-shell and higher excited states.

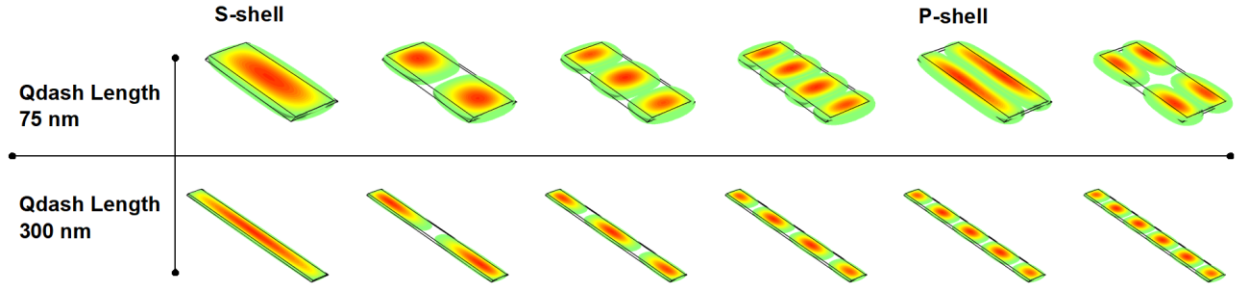


Figure 5.5 The evolution of the 3D probability density functions (PDFs) for electron states in Qdashes of lengths 75 nm and 300 nm.

The three-dimensional probability density functions (PDFs) shown in Fig. 5.5 further illustrate this behavior. For a shorter Qdash, such as 75 nm, a limited number of discrete S-like and P-like states are observed, separated by relatively large energy gaps. As the dash length increases to 300 nm, additional intermediate states emerge between the conventional S and P shells. These states resemble quasi-one-dimensional subbands arising from longitudinal confinement relaxation. The increased density of states enhances intradash carrier relaxation by providing multiple intermediate levels through which carriers can cascade toward the ground state.

This mini-band ladder effect has two important implications. First, it facilitates faster intradash carrier transport, potentially improving modulation dynamics. Second, it increases the spatial extension of electron wavefunctions along the elongation direction, thereby enhancing the possibility of overlap with neighboring Qdashes when lateral spacing is small. In contrast, heavy-hole states remain more localized due to their larger effective mass and stronger confinement, leading to less pronounced delocalization along the dash length.

The isolated-Qdash analysis therefore establishes a crucial baseline: optical transition energy is primarily governed by height and width, while dash length mainly affects the density and spatial extension of electronic states. These characteristics suggest that lateral coupling is likely to be

dominated by electron tunneling and strongly influenced by interdash spacing and size similarity. The following section examines these lateral coupling mechanisms in detail.

5.4 Lateral Interdash Tunneling Mechanisms

To investigate lateral coupling between adjacent quantum dashes, a parallel Qdash pair model is constructed, as illustrated in Fig. 5.6. In this configuration, two Qdashes are positioned side by side along the elongation direction, with a controllable edge-to-edge separation distance d . The left Qdash is assigned a lower optical transition energy, while the right Qdash has a slightly higher transition energy. This configuration reflects the realistic situation in self-assembled ensembles, where morphological variations lead to non-identical neighboring structures.

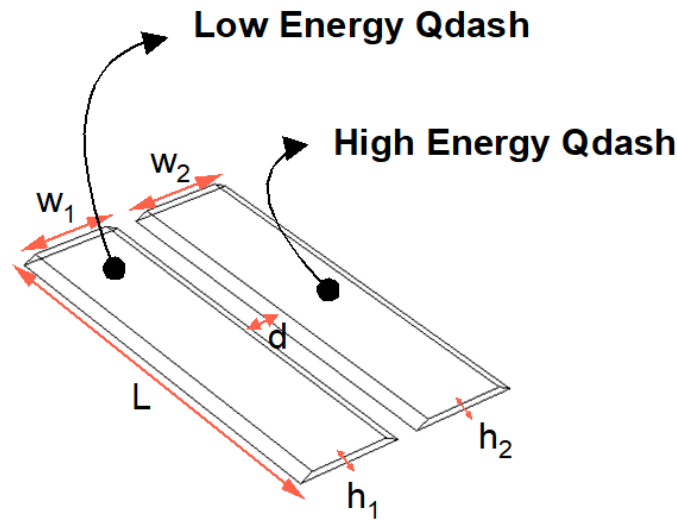


Figure 5.6 Diagram of simulated Qdash pair.

Fig. 3. The 1D wave function along $[0 -1 1]$ direction and 3D PDF visualizations for (d) strong coupling case, (e) weak coupling case. (f)

Lateral coupling primarily manifests through carrier tunneling from the higher-energy Qdash to the lower-energy Qdash. The tunneling strength depends on two key factors: the spatial overlap

of the carrier wavefunctions and the resonance condition between their eigenstate energies. When the ground-state energies of neighboring Qdashes are closely matched, strong same-shell (S–S) tunneling can occur. When the energy mismatch increases, coupling may instead proceed through heteroshell channels, such as S–P tunneling.

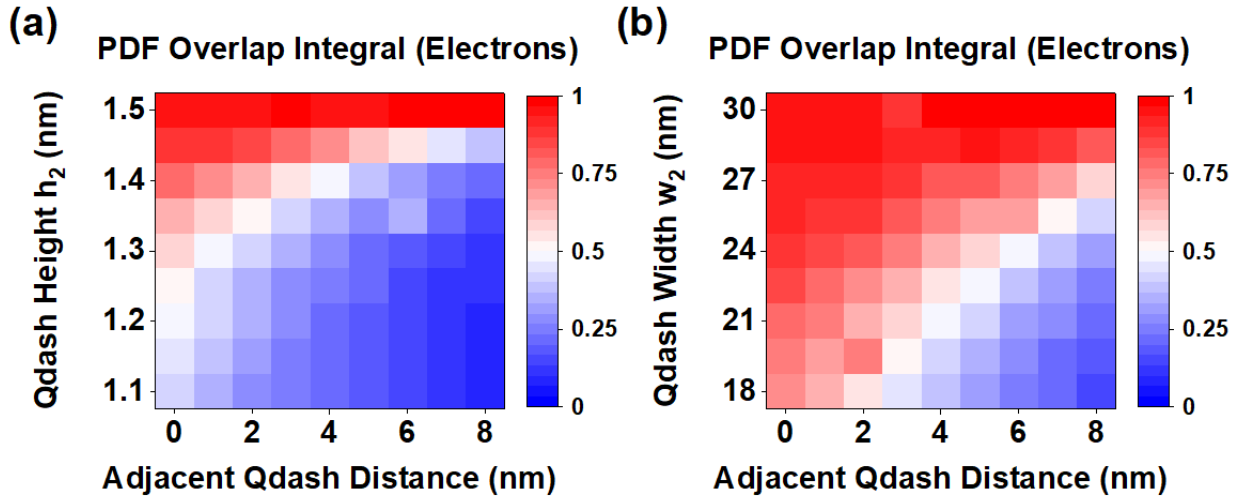


Figure 5.7 The change of ground-state electron PDFs overlap integral as function of (a) the height of the high-emission-energy Qdash and the interdash distance, (b) the width and the interdash distance.

The calculated overlap of electron ground-state probability density functions as a function of Qdash dimensions and separation distance is shown in Fig. 5.7(a) and Fig. 5.7(b). For fixed spacing, decreasing the height of the higher-energy Qdash increases the energy difference between adjacent structures. This energy detuning weakens the resonance condition and reduces wavefunction overlap. A similar trend is observed when reducing the width of the neighboring Qdash, although the sensitivity to width variation is less pronounced than that to height variation. These results confirm that size inhomogeneity reduces lateral coupling strength by breaking energy resonance between neighboring states.

The influence of spatial separation is equally important. For fixed Qdash dimensions, increasing the interdash distance significantly reduces wavefunction overlap. When the spacing is small, such as 3 nm, and the ground-state energy difference is minimal (on the order of a few meV), the electron wavefunctions become partially delocalized across both Qdashes, as shown in Fig. 5.8(a). In this strong-coupling regime, the S-shell states form hybridized bonding-like states spanning both structures. In contrast, when the spacing increases to 8 nm or the energy difference becomes larger, the wavefunctions remain strongly localized within individual Qdashes, as shown in Fig. 5.8(b), indicating weak coupling.

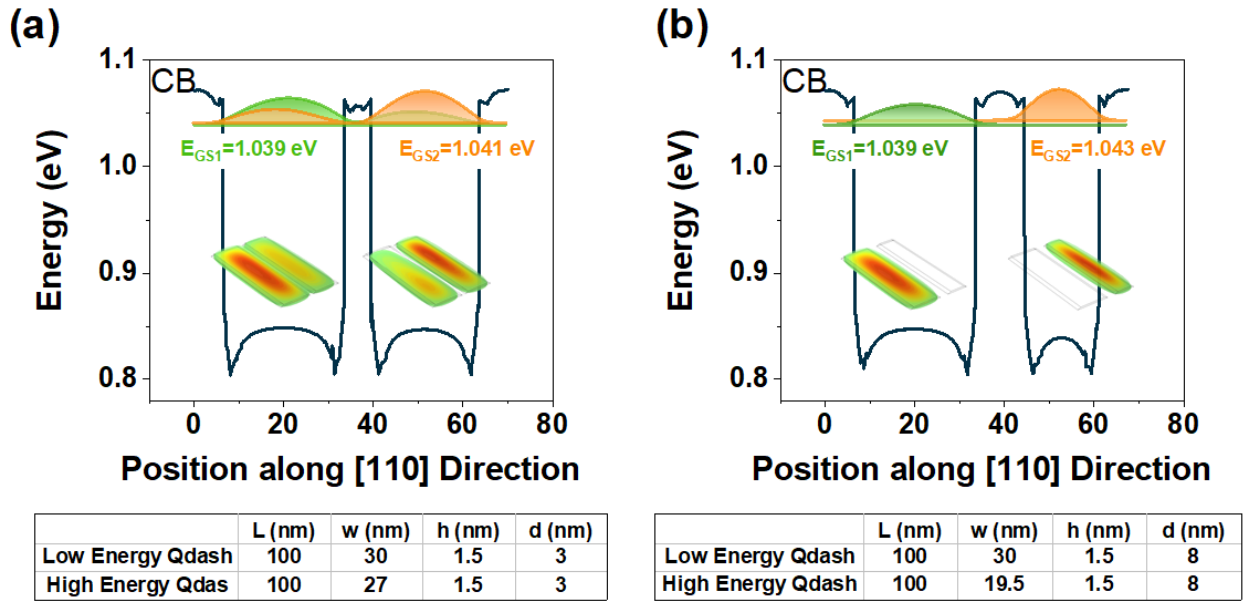
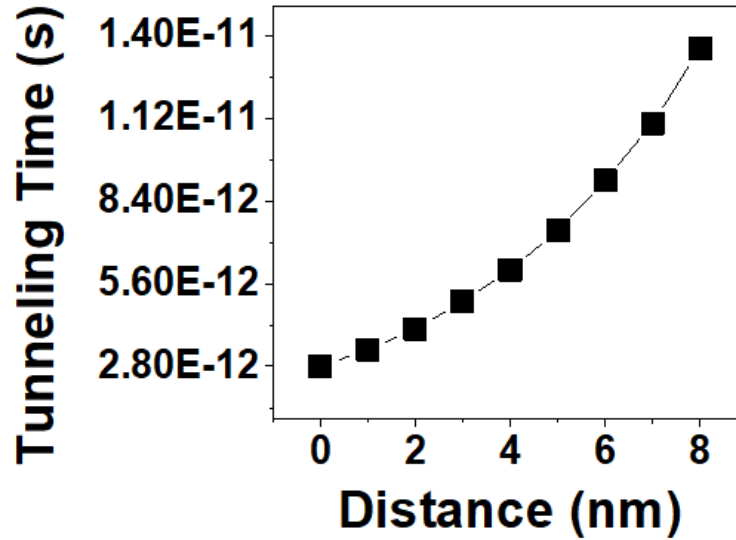


Figure 5.8 The 1D wave function along $[0 -1 1]$ direction and 3D PDF visualizations for (d) strong coupling case, (e) weak coupling case.

The calculated same-shell tunneling time between ground states is plotted in Fig. 5.9. The tunneling time increases exponentially with interdash distance, rising from a few picoseconds at near-zero spacing to more than ten picoseconds at 8 nm separation. This exponential dependence reflects the evanescent decay of wavefunctions within the barrier region. For realistic morphological statistics, the average tunneling time is on the order of a few picoseconds,

comparable to intradash carrier relaxation times. This suggests that lateral electron tunneling can significantly influence carrier redistribution within the Qdash ensemble.



	L (nm)	w (nm)	h (nm)	d (nm)
Low Energy Qdash	100	25	1.5	0~8
High Energy Qdash	100	25	1.1	0~8

Figure 5.9 the same-shell tunneling time change with interdash distance.

In contrast to electrons, heavy-hole states exhibit much weaker lateral coupling. Figures 5.10(a) and 5.10(b) show the overlap of heavy-hole ground-state wavefunctions under similar conditions. Significant overlap occurs only when neighboring Qdashes are nearly identical in size and extremely closely spaced. Even small geometric differences or modest increases in spacing suppress heavy-hole coupling. This behavior arises from the larger effective mass of heavy holes and the deeper valence band confinement in the InAs/InGaAsP system. As a result, heavy-hole wavefunctions remain tightly localized within individual Qdashes, and lateral hole tunneling is negligible under typical conditions.

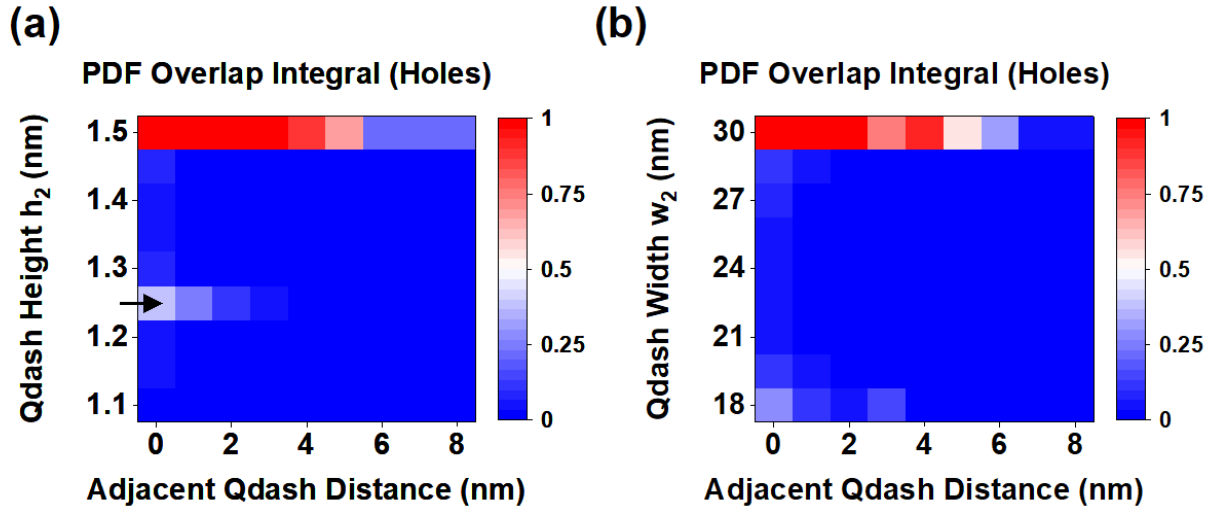


Figure 5.10 The change of heavy hole ground-state PDFs overlap integral as function of (a) the height of the high-emission-energy Qdash and the interdash distance, (b) the width and the interdash distance.

Although same-shell S–S tunneling is the most straightforward coupling pathway, heteroshell tunneling can also occur. In particular, S–P tunneling becomes possible when the ground-state energy of one Qdash aligns with an excited-state energy of its neighbor. An example of such heteroshell resonance is illustrated in Fig. 5.11(a) and Fig. 5.11(b). In this case, the S-shell state of the higher-energy Qdash aligns with a P-shell state of the lower-energy Qdash, enabling partial wavefunction overlap despite size asymmetry [105]. The calculated S–P tunneling time, shown in Fig. 5.5, increases more gradually with interdash distance compared with S–S tunneling. This indicates that heteroshell coupling is less sensitive to energy mismatch and spatial separation, making it a robust transport pathway in realistic, imperfectly aligned Qdash ensembles.

The lateral tunneling analysis reveals three important conclusions. First, electron states dominate lateral coupling due to their lighter effective mass and shallower confinement. Second, coupling strength depends strongly on both energy resonance and spatial proximity. Third, heteroshell tunneling provides an additional transport channel even when same-shell resonance is

weak. These mechanisms collectively enable carrier redistribution across neighboring Qdashs and may significantly modify the effective gain dynamics of Qdash-based devices.

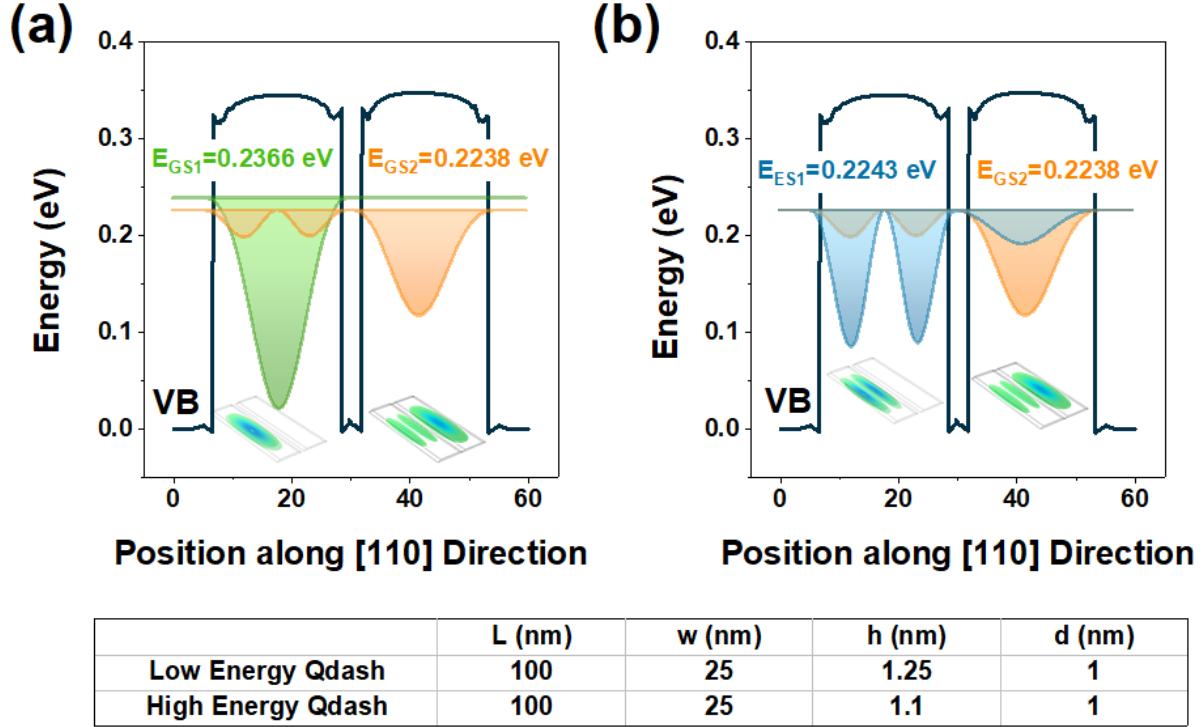


Figure 5.11 The 1D wave function along $[0 -1 1]$ direction and 3D PDF visualizations for (c) the same-shell (S-S) resonance, (e) hetero-shell (S-P) resonance.

In the following section, the impact of this lateral carrier redistribution on ensemble occupation and laser performance is examined using the travelling-wave time-domain framework.

5.5 Carrier Redistribution Induced by Lateral Tunneling

The microscopic tunneling processes described in the previous section directly influence carrier dynamics within the Qdash ensemble. To evaluate this effect at the device level, the tunneling mechanism is incorporated into the carrier rate equations of the travelling-wave time-domain model introduced in Chapter 3. Rather than treating all Qdashs as a single homogeneous

population, the ensemble is divided into two representative subgroups: a low-energy subgroup (GS1) and a high-energy subgroup (GS2). These two subgroups correspond to Qdashes with slightly different ground-state transition energies arising from morphological variation.

In the absence of lateral coupling, carriers captured into the wetting layer and subsequently relaxed into Qdash states populate GS1 and GS2 independently, with occupation determined primarily by capture, escape, and stimulated recombination processes. When lateral tunneling is included, an additional carrier transfer channel is introduced between GS2 and GS1. Specifically, electrons in the higher-energy subgroup may tunnel into the lower-energy subgroup with a characteristic tunneling time constant τ_{tunnel} . This additional transfer term modifies the carrier rate equations by introducing a redistribution mechanism that tends to equalize quasi-Fermi levels across neighboring Qdashes.

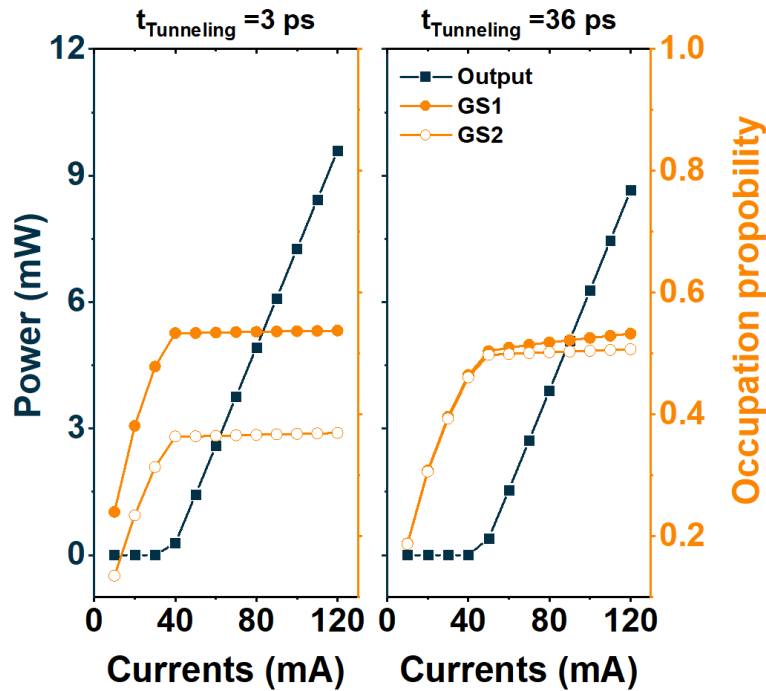


Figure 5.12 The density of state occupation probabilities of Qdashes under fast and slow tunneling rates for F-P laser with a 1500 μm cavity.

The physical consequence of this tunneling channel is illustrated in Fig. 5.12, which shows the density-of-states occupation probabilities under different tunneling times. When tunneling is fast, on the order of a few picoseconds, carriers injected into the active region are efficiently transferred from GS2 to GS1. As a result, the low-energy subgroup exhibits significantly higher occupation compared with the high-energy subgroup at the same injection level. This redistribution enhances the population inversion of GS1, which typically provides the dominant contribution to optical gain near the lasing wavelength.

In contrast, when tunneling is slow, carriers remain more evenly distributed between GS1 and GS2. In this regime, each subgroup behaves more independently, and the buildup of inversion in the dominant gain channel requires higher injection current. The redistribution efficiency therefore depends critically on the ratio between tunneling time and other carrier transport times, such as intradash relaxation and capture from the wetting layer.

It is important to note that lateral tunneling primarily affects electron populations, as heavy-hole states remain largely localized. Consequently, the redistribution mechanism mainly alters the electron quasi-Fermi level alignment between neighboring Qdashes. This asymmetry does not invalidate the gain enhancement mechanism, since stimulated recombination is strongly influenced by electron occupation in the conduction band. However, it does imply that lateral coupling modifies carrier balance rather than creating fully delocalized excitonic states across the ensemble.

The introduction of lateral tunneling into the rate equations therefore provides a physically consistent pathway linking microscopic wavefunction overlap to macroscopic carrier redistribution. The next section examines how this redistribution influences laser threshold behavior in different cavity configurations.

5.6 Influence of Lateral Coupling on Laser Threshold and Device Performance

Having established how lateral tunneling redistributes carriers between Qdash subgroups, its influence on laser performance can now be evaluated. The primary figure of merit considered here is the threshold current, which reflects the efficiency with which injected carriers contribute to modal gain. The calculated power–current (P–I) characteristics for Fabry–Pérot (F–P) lasers with different tunneling times are shown in Fig. 5.13.

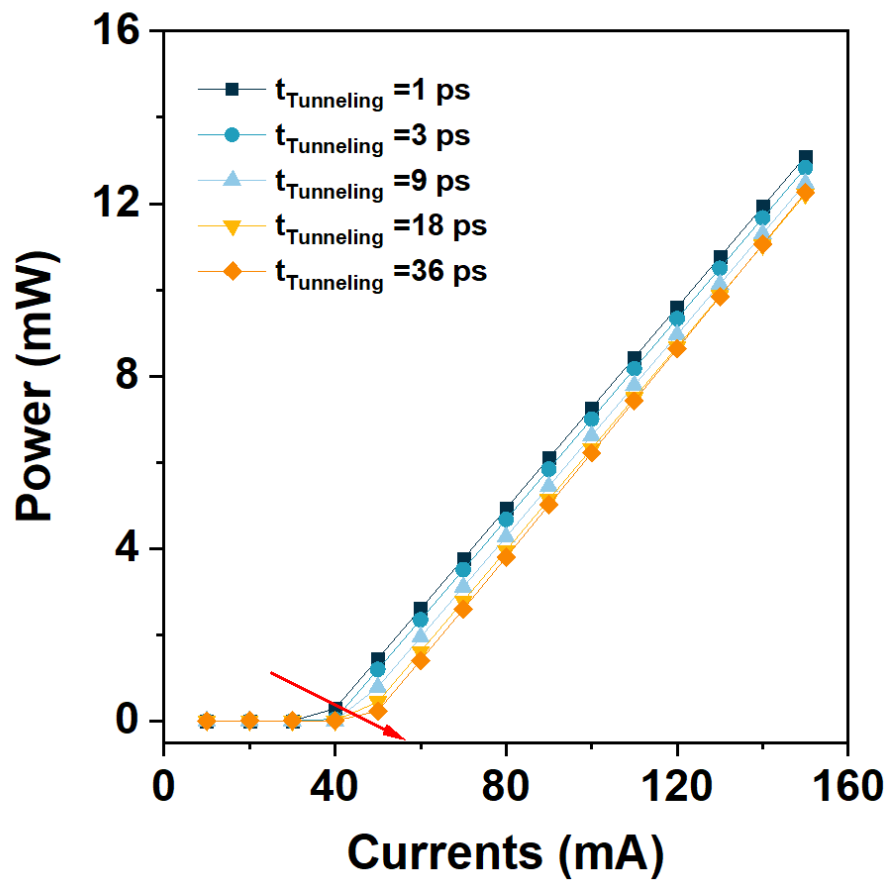


Figure 5.13 The P-I curves change with different tunneling rate for F-P laser with a 1500 μm cavity.

For a long-cavity F–P laser with a cavity length of 1500 μm , a clear dependence on tunneling time is observed. When the tunneling process is fast, with a time constant on the order of 1–3 ps, the threshold current is significantly reduced compared with the slow-tunneling case. As the tunneling time increases toward several tens of picoseconds, the P–I curve gradually approaches the uncoupled limit, and further increases in tunneling time produce negligible additional change. This behavior confirms that efficient carrier transfer from high-energy Qdashes to low-energy Qdashes enhances population inversion in the dominant gain channel, allowing threshold to be reached at lower injection levels.

The underlying mechanism can be understood in terms of carrier redistribution efficiency. In long-cavity devices, the modal volume is relatively large and the threshold gain requirement is modest. Under fast tunneling conditions, carriers injected into higher-energy subgroups are rapidly transferred to the lower-energy subgroup, where the optical gain is strongest. This concentration of carriers accelerates the buildup of inversion and reduces the injection current required to achieve threshold. In contrast, when tunneling is slow, carriers accumulate more evenly across subgroups, and higher injection levels are necessary to achieve sufficient gain in the dominant lasing channel.

The dependence of tunneling benefit on cavity length is illustrated in Fig. 5.14. As the cavity length decreases from 1500 μm to 1000 μm and 500 μm , the threshold reduction induced by fast tunneling becomes progressively smaller. In shorter cavities, the required threshold gain increases due to higher mirror loss. The active region volume is also reduced, and carrier density becomes higher at threshold. Under these conditions, the relative advantage provided by redistribution diminishes because other processes—such as carrier leakage and non-radiative recombination—become more significant.

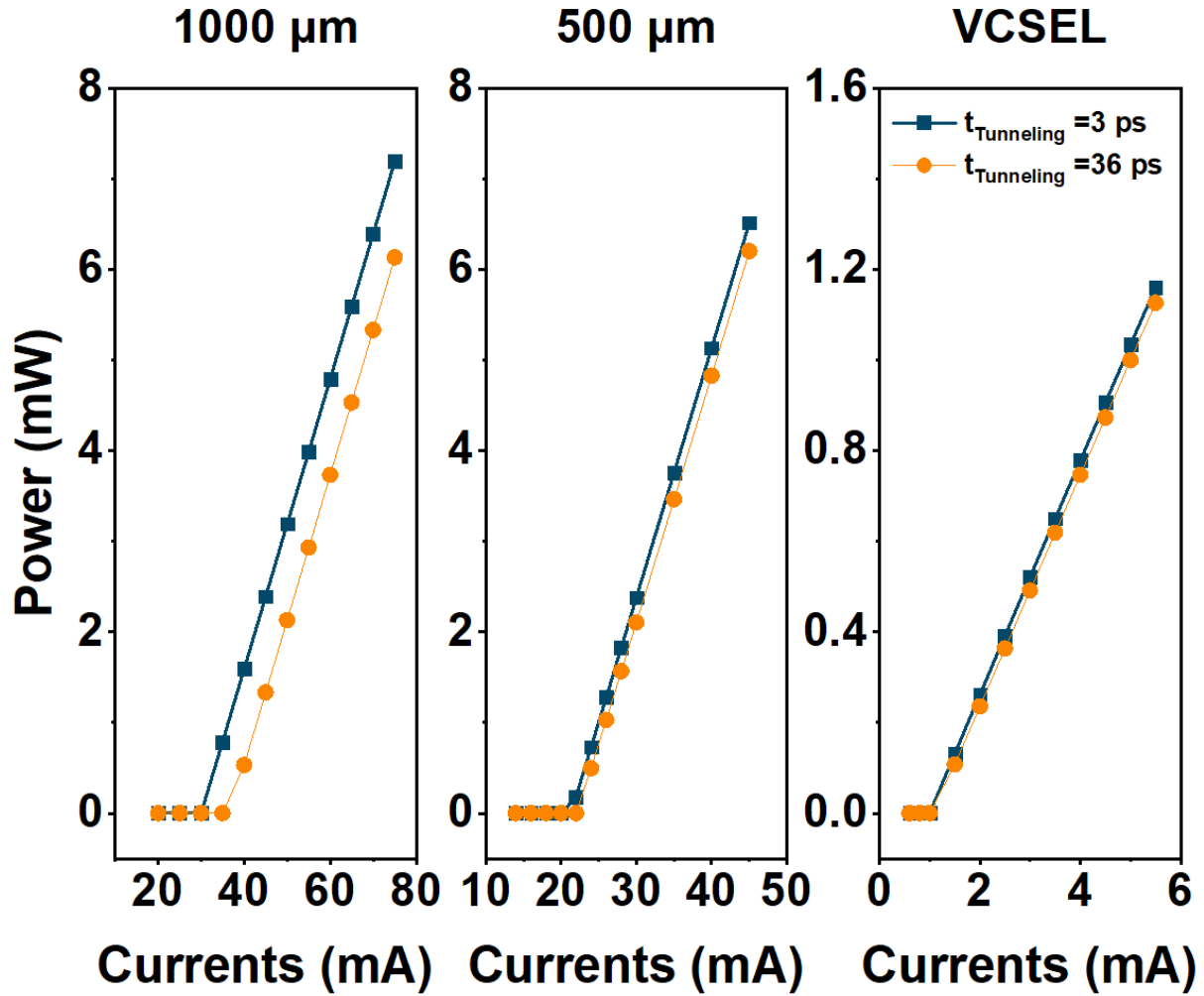


Figure 5.14 P-I curves under fast and slow tunneling rates for F-P laser with different cavity lengths and $2\text{-}\lambda$ cavity VCSEL.

The limiting case is the vertical-cavity surface-emitting laser (VCSEL), where the cavity length is extremely short and the optical confinement is strong. As shown in Fig. 5.14, the P-I curves of VCSELs exhibit only minor sensitivity to tunneling time. Although fast tunneling still redistributes carriers toward the low-energy subgroup, the high carrier density required for threshold in such small-volume cavities enhances non-radiative mechanisms, including Auger recombination and carrier escape. The gain improvement provided by redistribution is therefore partially offset by increased loss channels. The occupation probabilities shown in Fig. 5.15 confirm

that while GS1 occupancy increases under fast tunneling, the benefit does not translate into substantial threshold reduction.

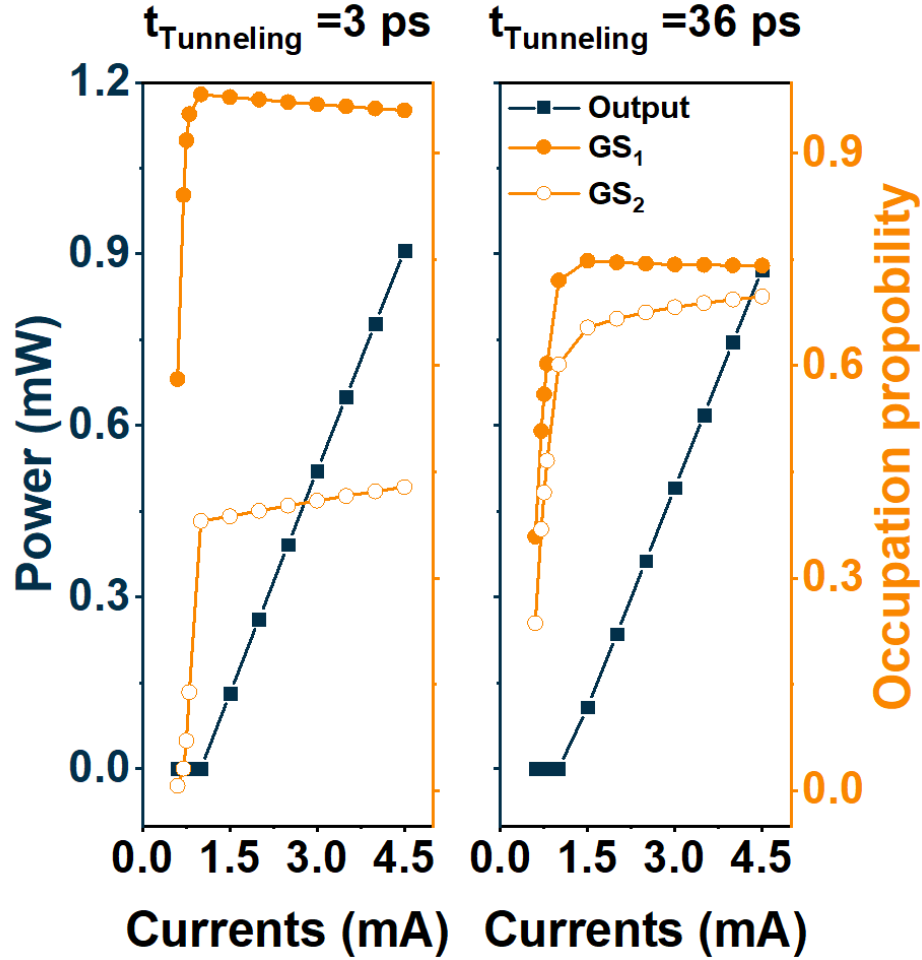


Figure 5.15 the density of state occupation probabilities of Qdashes under fast and slow tunneling rates for 2- λ cavity VCSEL.

These results demonstrate that the influence of lateral coupling is strongly device-dependent. In large-volume F-P lasers, efficient interdash tunneling enhances carrier transport and reduces threshold current by improving gain utilization. In contrast, in small-volume VCSELs, the impact of tunneling is limited because high carrier density and non-radiative losses dominate threshold behavior.

From a design perspective, this analysis highlights the importance of matching material morphology to device architecture. For long-cavity and broadband edge-emitting lasers, moderate lateral coupling may be beneficial and can be exploited through controlled Qdash density and spacing. For compact VCSEL devices, however, minimizing excessive lateral coupling may help avoid unnecessary carrier redistribution and associated non-radiative penalties. Thus, lateral coupling should not be universally suppressed or enhanced; instead, it should be engineered according to the targeted device configuration.

5.7 Conclusions

In this chapter, the lateral coupling effects in InAs/InGaAsP quantum-dash structures have been systematically investigated, spanning from microscopic electronic structure to macroscopic laser performance. Beginning with realistic morphological statistics, it was shown that Qdash ensembles in this material system exhibit relatively small lateral spacing and elongated geometries, conditions that make lateral electron tunneling physically plausible. Isolated-Qdash analysis established that while optical transition energy is primarily governed by dash height and width, the dash length strongly influences the density and spatial extension of electronic states, thereby affecting potential wavefunction overlap between neighboring structures.

The lateral interdash coupling mechanisms were analyzed using a parallel Qdash pair model. Electron states were found to dominate the coupling process due to their lighter effective mass and shallower confinement. Same-shell (S–S) tunneling occurs under strong resonance conditions with small energy mismatch and short interdash distance, while heteroshell (S–P) tunneling provides a more robust coupling pathway under realistic morphological variation. In contrast, heavy-hole states remain strongly localized because of deeper valence-band confinement and larger effective mass, resulting in negligible lateral hole tunneling under typical conditions. These findings indicate that lateral coupling primarily modifies electron redistribution rather than forming fully delocalized excitonic states.

By incorporating tunneling terms into the carrier rate equations of the travelling-wave time-domain model, the impact of lateral coupling on device performance was evaluated. Efficient tunneling enhances carrier redistribution from high-energy to low-energy Qdashes, improving gain utilization and reducing threshold current in long-cavity Fabry–Pérot lasers. However, the benefit diminishes as cavity volume decreases, and in compact VCSEL configurations the effect becomes marginal due to the dominance of high carrier density and non-radiative recombination processes. The results therefore demonstrate that lateral coupling is not intrinsically beneficial or detrimental; rather, its influence depends strongly on device architecture and operating regime.

Overall, this chapter establishes lateral interdash coupling as a morphology-dependent transport mechanism that can significantly influence carrier dynamics in Qdash-based devices. Together with the vertical coupling effects discussed in Chapter 4, the findings reveal that both growth-direction and in-plane interactions must be considered when engineering quantum-dash gain materials. In the next chapter, these coupling principles will be leveraged to explore device-level optimization strategies aimed at threshold reduction and dynamic performance enhancement.

Chapter 6 Composition and Strain Engineering of Qdash

Active Regions for High-Speed C-Band VCSELs

6.1 Introduction

Long-wavelength vertical-cavity surface-emitting lasers operating in the C-band (around 1.55 μm) play a critical role in modern optical communication systems. The C-band coincides with the minimum loss window of silica fibers and offers low chromatic dispersion, making it the preferred wavelength range for metro networks, data centers, and emerging silicon photonic interconnect platforms. In addition to transmission advantages, C-band sources are highly attractive for integration with CMOS-compatible silicon photonics, enabling compact and energy-efficient on-chip optical communication.

Among various device architectures, wafer-fused VCSELs have emerged as a promising solution for long-wavelength operation. By combining InP-based active regions with GaAs/AlGaAs distributed Bragg reflectors (DBRs), wafer-fusion technology leverages the high optical gain of III–V quantum nanostructures and the superior reflectivity and thermal conductivity of GaAs-based mirrors. However, compared with short-wavelength GaAs-based VCSELs, C-band devices typically suffer from longer effective cavity lengths, higher photon lifetimes, and more complex current confinement structures, all of which can limit modulation bandwidth.

Improving the dynamic performance of long-wavelength VCSELs therefore requires simultaneous optimization of cavity properties and gain medium characteristics. While cavity shortening and mirror engineering can reduce photon lifetime, intrinsic material properties ultimately govern differential gain and carrier dynamics. Quantum dash active regions offer distinct advantages in this regard. Their reduced dimensionality provides enhanced carrier localization, improved temperature stability, and potentially higher differential gain compared

with quantum wells. However, designing Qdash structures for C-band operation introduces a fundamental trade-off: increasing Qdash height strengthens optical confinement and transition strength but induces a red shift that pushes emission toward the L-band.

This trade-off motivates the need for coordinated bandgap and strain engineering. Rather than limiting Qdash height to maintain wavelength, it is desirable to introduce blue-shifting mechanisms that restore C-band emission while preserving strong carrier confinement. In this chapter, a composition-engineered Qdash design is proposed that combines slight P-alloying within the InAs Qdash and optimized confinement layers consisting of an InP first capping layer and a 1.10Q InGaAsP second capping layer. Using the multi-physics simulation framework developed in Chapter 3, we systematically evaluate how these modifications influence optical confinement, dipole strength, differential gain, and modulation bandwidth.

Unlike the previous chapters, which focused primarily on coupling mechanisms in nanostructures, this chapter translates microscopic band-structure engineering into device-level dynamic performance improvement. The goal is not to demonstrate record-breaking bandwidth, but to identify physically grounded design principles that can guide future experimental optimization of high-speed C-band Qdash VCSELs.

6.2 Wafer-Fused VCSEL Architecture and Optical Mode Characteristics

The device investigated in this chapter follows a conventional wafer-fused C-band VCSEL architecture, as illustrated in Fig. 6.1. The bottom distributed Bragg reflector (DBR) consists of 33.5 AlGaAs/GaAs pairs, while the top DBR contains 22.5 pairs. This asymmetric mirror configuration balances optical reflectivity and output coupling efficiency. The active region is embedded within a three- λ -thick InP-lattice-matched InGaAsP cavity. Carrier injection is achieved through an InGaAs-based buried tunnel junction (BTJ), which provides lateral current confinement while maintaining optical transparency near the cavity center.

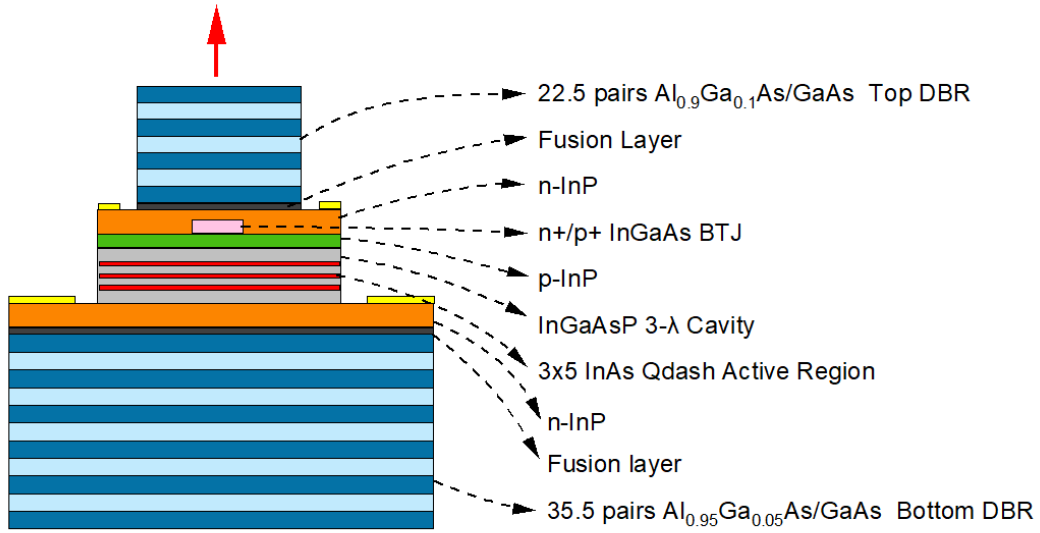


Figure 6.1 Schematic of the wafer-fused C-band VCSEL structure.

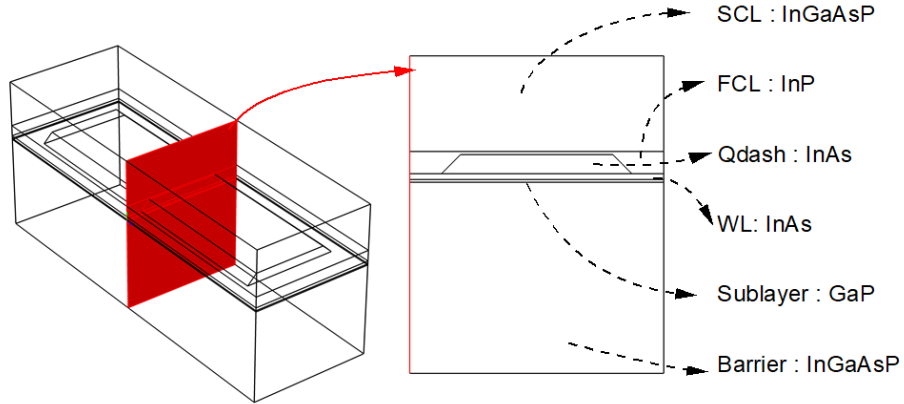


Figure 6.2 Material composition and geometric configuration of the InAs Qdash active region.

The Qdash gain medium, shown in Fig. 6.2, consists of three stacks of five InAs Qdash layers. Each Qdash has a nominal width of 30 nm and a length of 100 nm, consistent with experimentally reported structures. A thin GaP sublayer and an InAs wetting layer are included to reproduce realistic growth conditions. To enable flexible bandgap and strain engineering, a double-capping

structure is adopted. The first capping layer (FCL) is selected from candidate materials such as InGaAsP, InP, or InGaP, while the second capping layer (SCL) consists of lattice-matched InGaAsP with adjustable composition. Together, these layers determine both the conduction-band offset and the strain distribution surrounding the Qdash.

The optical properties of the cavity are analyzed using the eigenmode solver described in Chapter 3. The calculated longitudinal electric-field distribution is shown in Fig. 6.3. The fundamental cavity mode exhibits an eigenfrequency corresponding to a resonant wavelength of 1548.5 nm, well within the C-band. The standing-wave pattern clearly peaks in the central active region, ensuring strong overlap between the optical field and the Qdash ensemble. The buried tunnel junction is positioned slightly away from the field maximum to minimize absorption losses while preserving efficient current injection.

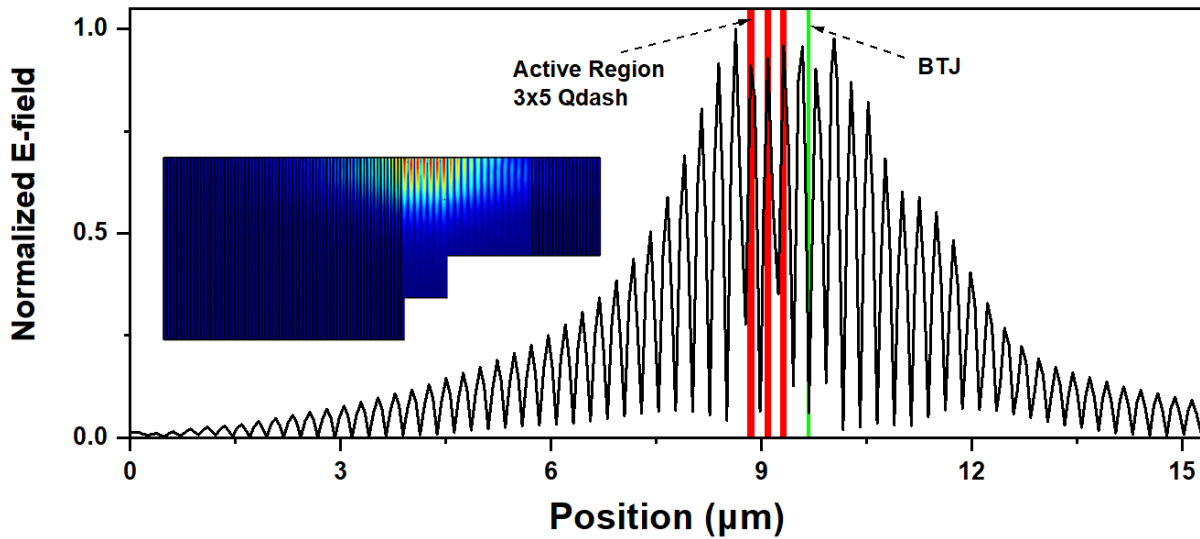


Figure 6.3 Optical characteristics of the VCSEL cavity: normalized longitudinal electric-field distribution, inset is standing-wave field pattern.

The complex eigenfrequency yields a cavity Q-factor of approximately 7.7×10^3 , consistent with the reflectivity of the fused AlGaAs/GaAs DBRs and the short effective cavity length characteristic of wafer-fused VCSELs. From the field distribution, the longitudinal and lateral confinement factors are extracted. These parameters quantify the overlap between the optical mode and the active region and directly influence the modal gain.

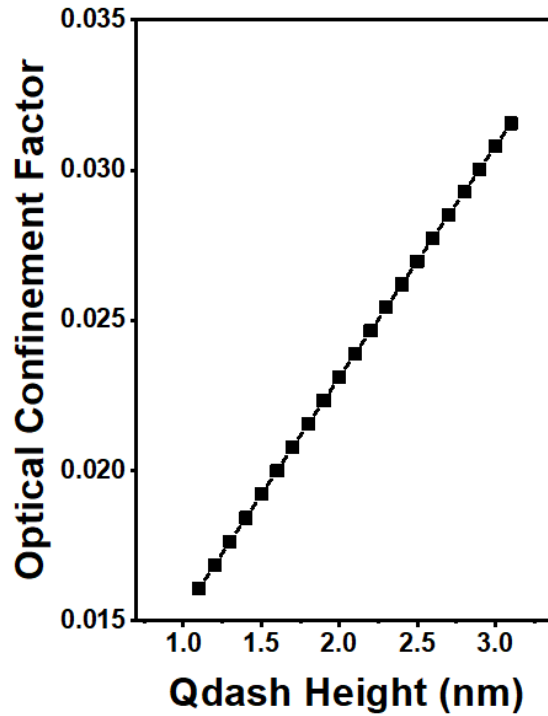


Figure 6.4 Optical characteristics of the VCSEL cavity: calculated optical confinement factor as a function of Qdash height.

Figure 6.4 shows the calculated optical confinement factor as a function of Qdash height. As the Qdash height increases from 1.1 nm to 3.1 nm, the confinement factor increases nearly linearly from 0.016 to approximately 0.032. Physically, increasing the Qdash height effectively increases the thickness of the active region and enhances mode–gain overlap. This improvement is beneficial

for achieving higher modal gain and larger differential gain. However, as discussed in the following section, increasing Qdash height simultaneously induces a strong red shift of the emission wavelength. Therefore, optical confinement enhancement must be carefully balanced against band-structure constraints to maintain C-band operation.

The cavity analysis presented here establishes two essential design considerations. First, the optical mode is well localized within the Qdash region, meaning that modifications of Qdash geometry and composition directly translate into changes in device performance. Second, increasing Qdash height is highly advantageous from a confinement perspective. This observation motivates the bandgap engineering strategies explored in the next section, where mechanisms for restoring C-band emission while preserving increased Qdash volume are examined in detail.

6.3 Bandgap and Strain Engineering for Emission Blue-Shifting

Designing InAs/InGaAsP quantum dashes for C-band emission requires careful balancing of quantum confinement and strain effects. In conventional InAs Qdash structures lattice-matched to InP, the ground-state transition wavelength is highly sensitive to dash height. Increasing the height enhances optical confinement and carrier localization, as shown in Section 6.2, but simultaneously reduces quantum confinement energy and intensifies strain-induced band shifts, resulting in a pronounced red shift. For heights exceeding approximately 2 nm, the emission rapidly moves toward the L-band, limiting the ability to exploit larger dash volumes for improved differential gain.

To enable increased Qdash height while preserving C-band emission, emission blue-shifting mechanisms must be introduced. Two primary strategies are considered in this work: modification of the confinement layers surrounding the Qdash and direct adjustment of the intrinsic Qdash bandgap through alloy engineering.

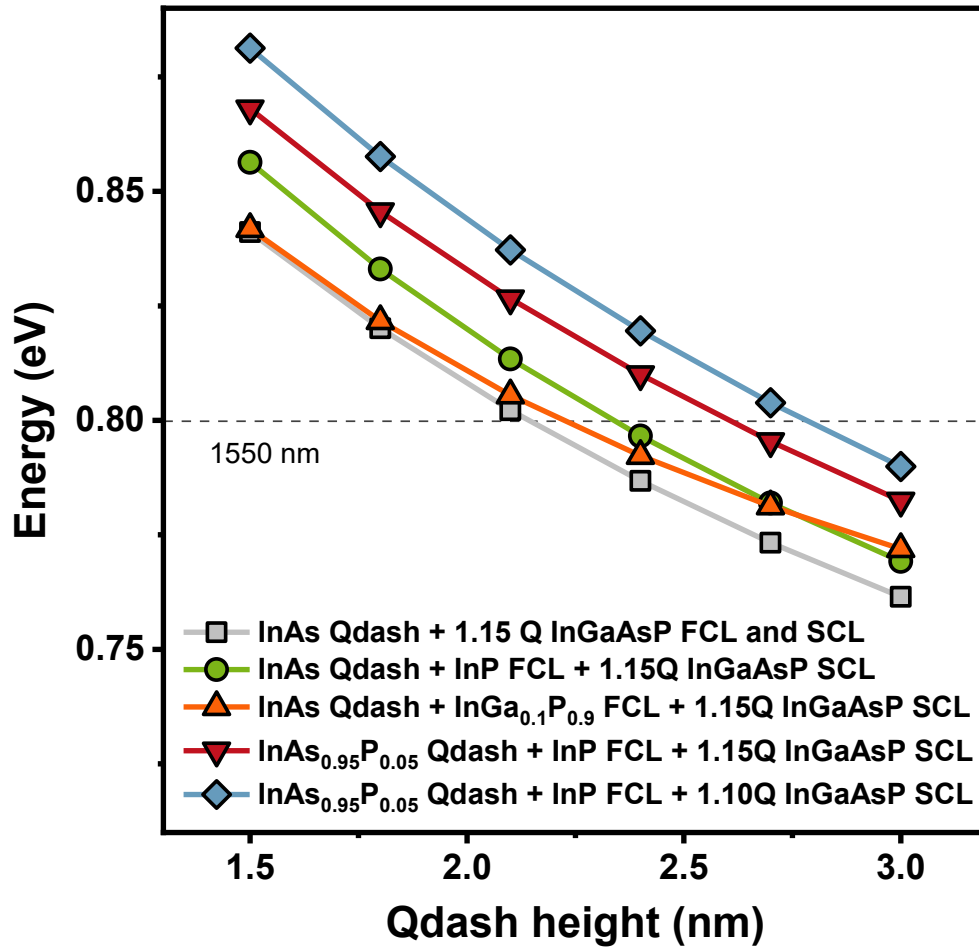


Figure 6.5 Ground-state transition energy versus Qdash height for various capping layer compositions.

The first approach involves replacing the first capping layer (FCL) with a higher-bandgap material. Figure 6.5 shows the calculated ground-state transition energies as a function of Qdash height for different FCL compositions. When the conventional 1.15Q InGaAsP FCL is replaced by InP or InGa_{0.1}P_{0.9}, a blue shift of the transition energy is observed. At first glance, InGa_{0.1}P_{0.9} would be expected to produce the strongest blue shift due to its larger bulk bandgap. However, the simulation results reveal that InP provides a more effective blue-shifting effect.

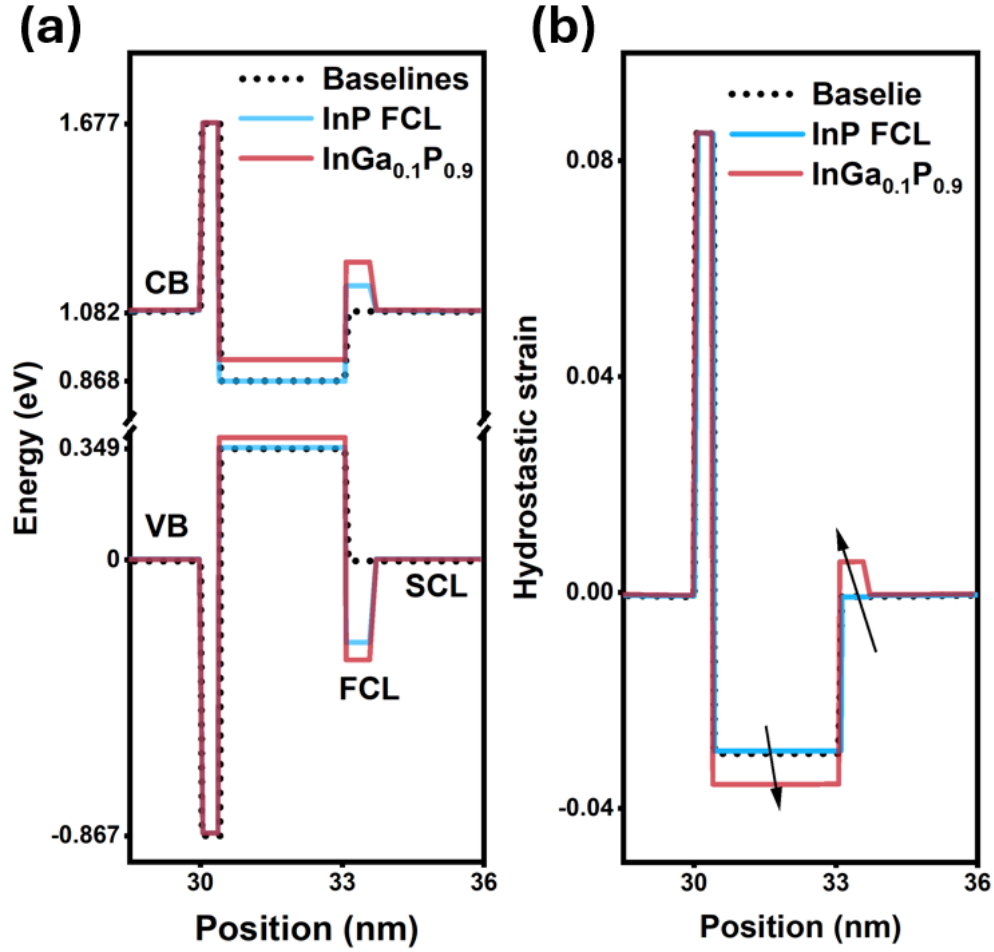


Figure 6.6 (a) Conduction band diagrams and (b) hydrostatic strain distributions comparing InP and InGa_{0.1}P_{0.9} FCLs.

This apparent contradiction can be understood by examining the conduction-band alignment and strain distribution. As shown in Fig. 6.6(a), the conduction-band offset at the InAs-InP interface is approximately 300 meV, while the offset at the InAs-InGa_{0.1}P_{0.9} interface is only marginally larger. The limited improvement in confinement arises from strain-induced band modification rather than bandgap values alone. The lattice constant of InGa_{0.1}P_{0.9} is smaller than that of InP, leading to increased compressive strain within the Qdash region. This enhanced compressive strain raises the conduction-band edge inside the Qdash while simultaneously lowering the conduction band of the tensile-strained FCL. The net effect reduces effective electron

confinement, partially offsetting the nominal advantage of the larger bandgap material. Figure 6.6(b) confirms that hydrostatic strain in the Qdash region is stronger when $\text{InGa}_{0.1}\text{P}_{0.9}$ is used, explaining the weaker-than-expected blue-shift performance.

These results highlight an important principle: emission wavelength engineering cannot rely solely on bulk bandgap values. The interplay between strain redistribution and band offsets must be considered self-consistently, as strain modifies both conduction and valence band edges.

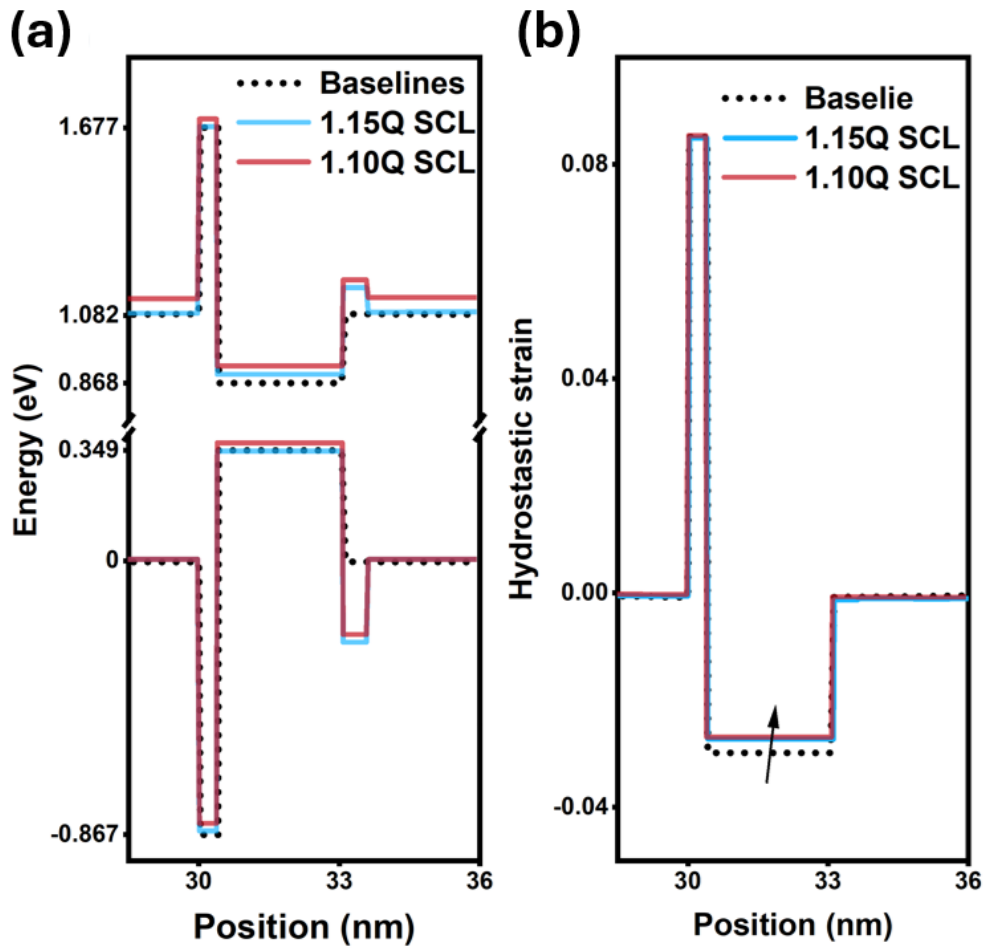


Figure 6.7 Conduction band profile and hydrostatic strain distributions for the P-alloyed $\text{InAs}_{0.95}\text{P}_{0.05}$ Qdash with 1.15Q and 1.10Q InGaAsP SCL.

The second blue-shifting strategy involves directly increasing the intrinsic bandgap of the Qdash material through slight phosphorus alloying. Introducing approximately 5% P into the InAs Qdash increases its bulk bandgap by roughly 23 meV. Figure 6.7(a) illustrates the conduction-band profiles for P-alloyed $\text{InAs}_{0.95}\text{Po}_{0.05}$ Qdashes combined with optimized confinement layers. The increased intrinsic bandgap directly raises the transition energy, producing a substantial blue shift.

In addition to modifying the bandgap, P incorporation slightly reduces the Qdash lattice constant. As shown in Fig. 6.7(b), this reduces the lattice mismatch between the Qdash and surrounding barrier, thereby decreasing compressive strain in the Qdash region. The reduced strain lowers the upward strain-induced shift of the conduction band inside the Qdash and increases the effective conduction-band offset with respect to the surrounding layers. Consequently, electron confinement is strengthened rather than weakened. This simultaneous increase in intrinsic bandgap and improvement in band offset makes P-alloying particularly effective.

Further enhancement is achieved by adjusting the composition of the second capping layer (SCL). Reducing the SCL composition from 1.15Q to 1.10Q InGaAsP increases the conduction-band offset between the Qdash and the barrier. The calculated ΔE_c increases from approximately 198 meV to 217 meV, further improving electron confinement. The combined effect of P-alloying and optimized double-capping enables substantial blue shifting while maintaining or even enhancing carrier confinement.

Taken together, these results demonstrate that coordinated bandgap and strain engineering provides a practical route to decoupling emission wavelength from Qdash height. By combining intrinsic bandgap tuning within the Qdash and optimized confinement layers that manage strain distribution, it becomes possible to increase dash height for stronger optical confinement without sacrificing C-band emission. In the next section, the influence of these modifications on optical transition strength and dipole matrix elements is examined in detail.

6.4 Confinement Enhancement and Optical Transition Strength

While emission wavelength determines spectral positioning, laser performance is strongly governed by optical transition strength. In particular, differential gain and modulation bandwidth depend sensitively on the electron–hole overlap and the dipole matrix element associated with the ground-state transition. Therefore, after establishing the mechanisms for emission blue-shifting, it is essential to examine how composition and strain engineering influence carrier confinement and transition strength.

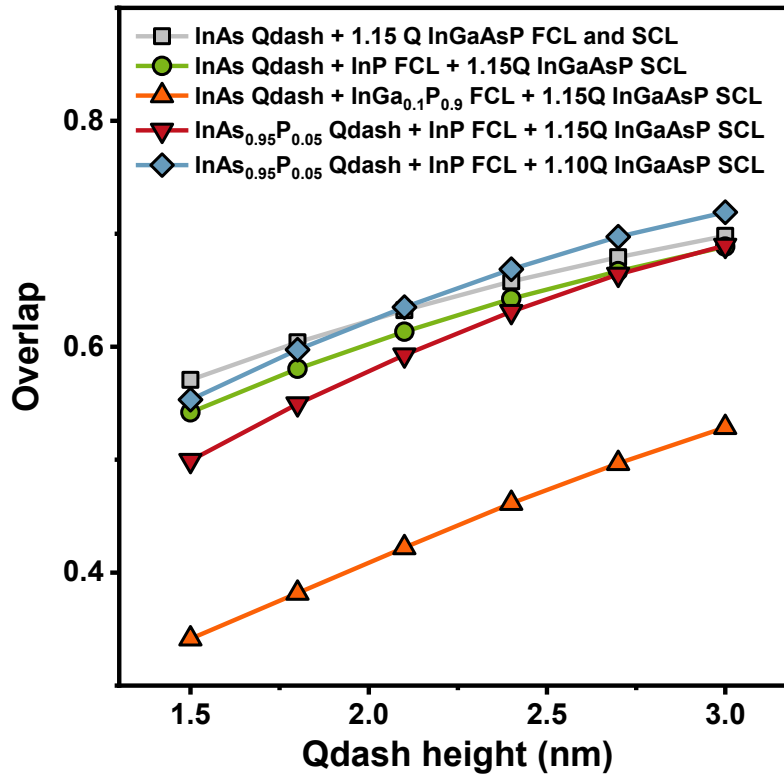


Figure 6.8 Ground-state electron–hole probability density overlap versus Qdash height.

Figure 6.8 presents the calculated ground-state electron–hole probability density overlap as a function of Qdash height for different confinement-layer configurations. For all material systems, increasing the Qdash height enhances the overlap. A taller Qdash strengthens vertical confinement,

reducing electron wavefunction leakage into the barrier and improving spatial overlap with hole states. However, significant differences are observed among the various capping-layer designs.

Structures employing an $\text{InGa}_{0.1}\text{P}_{0.9}$ first capping layer consistently exhibit reduced overlap compared with both the conventional InGaAsP barrier and the InP -based configuration. This reduction is directly linked to the strain-induced band modification discussed in Section 6.3. Although $\text{InGa}_{0.1}\text{P}_{0.9}$ has a larger bulk bandgap, the enhanced compressive strain in the Qdash region raises the conduction-band edge and weakens effective electron confinement. As a result, the electron wavefunction extends further into the surrounding barrier, decreasing overlap with the more localized heavy-hole wavefunction.

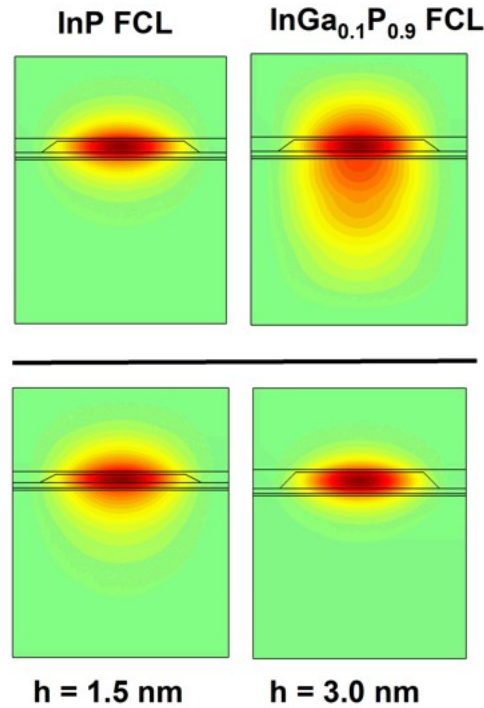


Figure 6.9 Cross-sectional ground-state electron probability density distributions. Top: same Qdash height with different FCL compositions. Bottom: same material composition with different Qdash heights.

This behavior is clearly illustrated in the electron probability density distributions shown in Fig. 6.9. For the $\text{InGa}_{0.1}\text{P}_{0.9}$ FCL case, the electron ground-state wavefunction exhibits noticeable penetration into the barrier region. In contrast, when an InP FCL is employed, stronger confinement keeps the electron wavefunction more tightly localized within the Qdash. The improved localization increases spatial overlap with hole states and enhances transition strength.

The effect of Qdash height can also be observed in Fig. 6.5(b). For a fixed material composition, increasing the Qdash height results in stronger vertical confinement and reduced wavefunction leakage. This confirms that taller Qdashes are beneficial for maximizing overlap, provided that emission wavelength can be properly managed through bandgap engineering.

The dipole matrix element, expressed in terms of dipole length, provides a direct measure of optical transition strength. Figure 6.5(c) compares the dipole lengths of different Qdash configurations engineered to emit at 1550 nm. The composition-engineered Qdash, incorporating slight P-alloying together with an InP FCL and a 1.10Q InGaAsP SCL, exhibits a substantially larger dipole length than the baseline InAs Qdash structure. This enhancement originates from two synergistic effects: strengthened electron confinement due to increased conduction-band offset, and improved electron–hole spatial overlap.

An increased dipole matrix element directly translates into higher material gain and enhanced differential gain, as the stimulated emission rate scales with the square of the transition matrix element. Therefore, the confinement improvements achieved through coordinated composition and strain engineering not only restore C-band emission for taller Qdashes but also strengthen light–matter interaction.

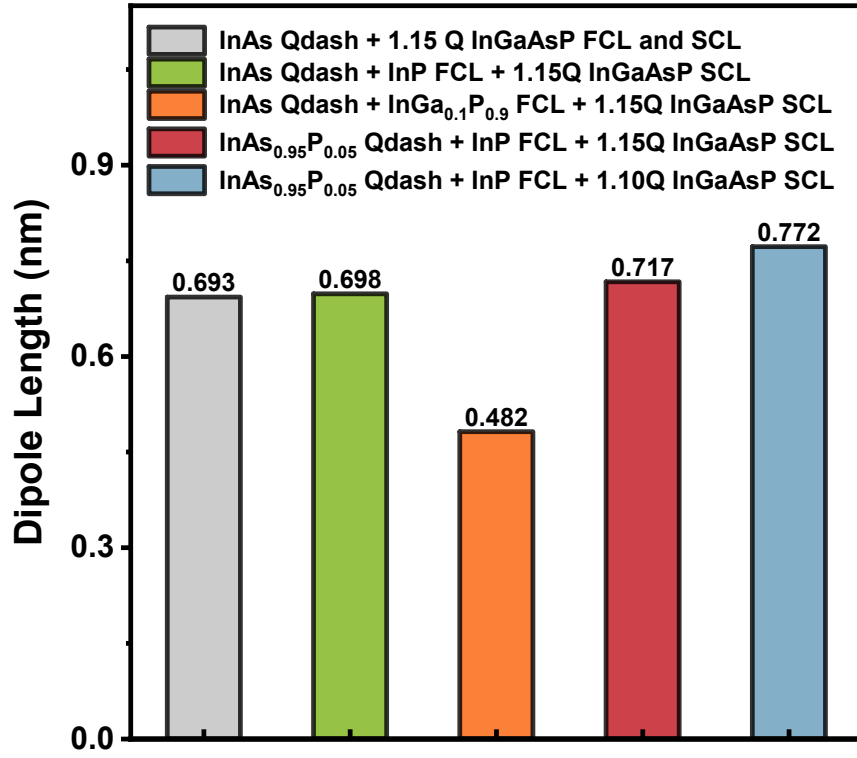


Figure 6.10 Dipole lengths at 1550 nm for different Qdash configurations.

In summary, the engineered Qdash structure simultaneously achieves three key advantages: controlled emission wavelength, enhanced electron confinement, and increased optical transition strength. These improvements collectively establish the foundation for the differential gain enhancement and modulation bandwidth increase demonstrated in the following sections.

6.5 Static Laser Characteristics and Differential Gain Enhancement

The influence of composition and confinement engineering on device-level performance is evaluated using the travelling-wave time-domain model described in Chapter 3. Two structures are compared throughout this section: a baseline device employing a conventional InAs Qdash active region with a lattice-matched 1.15Q InGaAsP barrier, and a composition-engineered device

incorporating a P-alloyed $\text{InAs}_{0.95}\text{Po}_{0.05}$ Qdash surrounded by an InP first capping layer and a 1.10Q InGaAsP second capping layer.

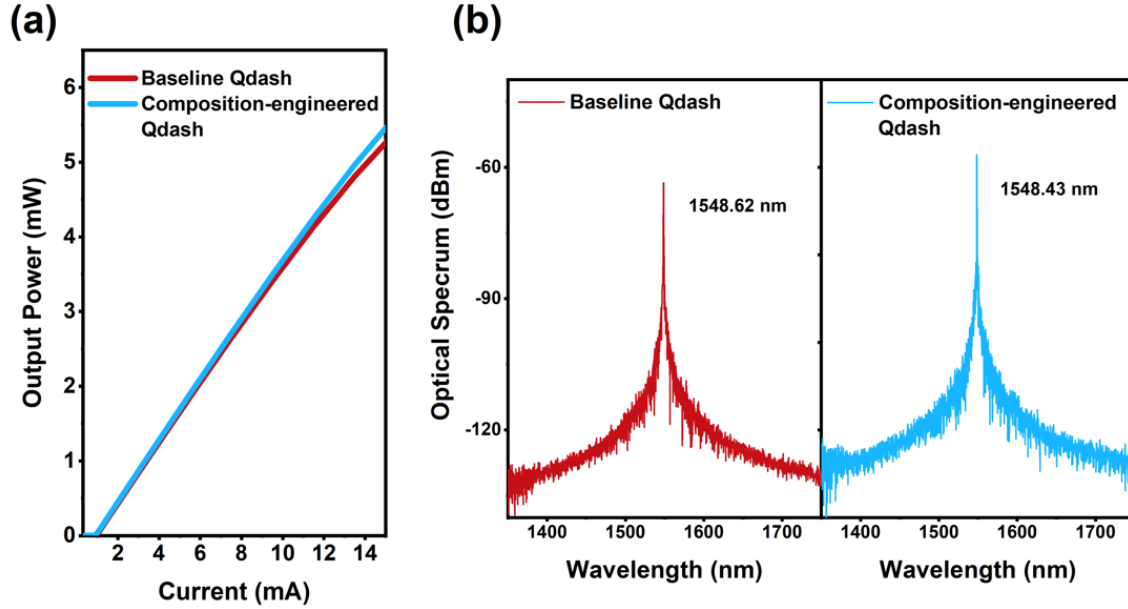


Figure 6.11 Static lasing performance calculated using the TDTW model. (a) P-I characteristics, (b) Lasing spectra.

Figure 6.11(a) shows the calculated power–current (P–I) characteristics of the two devices. Both structures exhibit similar threshold currents and comparable output power levels. This indicates that the engineering strategy does not introduce significant penalty in terms of modal gain or threshold condition. The comparable threshold behavior arises because the overall material gain spectra remain centered near the lasing wavelength in both cases, and the cavity parameters are identical.

The corresponding emission spectra are presented in Fig. 6.11(b). The engineered device exhibits a modest blue shift relative to the baseline structure, consistent with the band-structure analysis discussed in Section 6.3. Importantly, the emission remains well within the C-band

window, confirming that the combination of P-alloying and optimized confinement layers successfully compensates for the red shift associated with increased Qdash height.

While the static output power characteristics are similar, a distinct improvement is observed in the differential gain. Figure 6.6(c) shows the material gain and differential gain spectra at an injection current of 7 mA. Although the peak material gain near the lasing wavelength differs only slightly between the two structures, the differential gain of the composition-engineered Qdash is enhanced by approximately 16% compared with the baseline device.

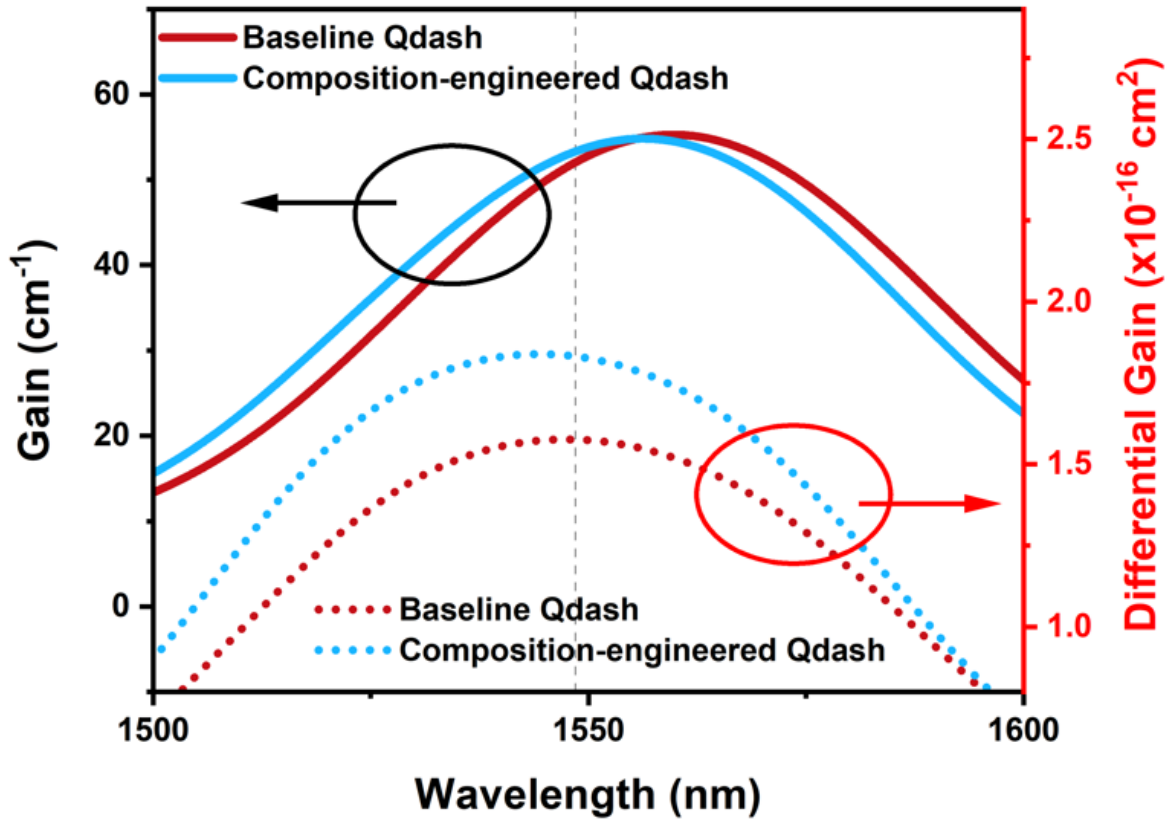


Figure 6.12 Static lasing performance calculated using the TDTW model: Gain and differential gain versus wavelength at 7 mA injection current.

This enhancement originates from the increased dipole matrix element and improved carrier confinement described in Section 6.4. Stronger electron localization increases the stimulated emission rate for a given carrier density, resulting in a steeper slope of gain versus carrier concentration. In other words, the gain responds more efficiently to carrier injection, which directly increases the relaxation-oscillation frequency and reduces damping in the modulation response.

It is important to emphasize that the improvement arises from intrinsic material properties rather than changes in cavity design. The optical confinement factor and Q-factor remain comparable between the two structures; thus, the observed differential gain enhancement is primarily a consequence of bandgap and strain engineering within the Qdash region.

The static performance analysis therefore demonstrates that the proposed composition-engineered design achieves emission wavelength control and stronger light–matter interaction without degrading threshold or output power. The enhanced differential gain established in this section provides the fundamental basis for improved dynamic modulation characteristics, which are examined in the following section.

6.6 Dynamic Modulation Performance and Bandwidth Enhancement

The enhancement in differential gain demonstrated in Section 6.5 directly influences the modulation response of the VCSEL. To quantify this impact, both small-signal and large-signal dynamic characteristics are evaluated using the travelling-wave time-domain model. The comparison focuses on the baseline Qdash VCSEL and the composition-engineered device under identical cavity and bias conditions.

Figure 6.13(a) and Fig. 6.13(b) show the calculated small-signal modulation responses at various injection currents. For the baseline device, the -3 dB modulation bandwidth reaches approximately 11.2 GHz. In contrast, the composition-engineered VCSEL achieves a -3 dB

bandwidth of 13.4 GHz under comparable bias conditions. This corresponds to a relative bandwidth increase of nearly 20%.

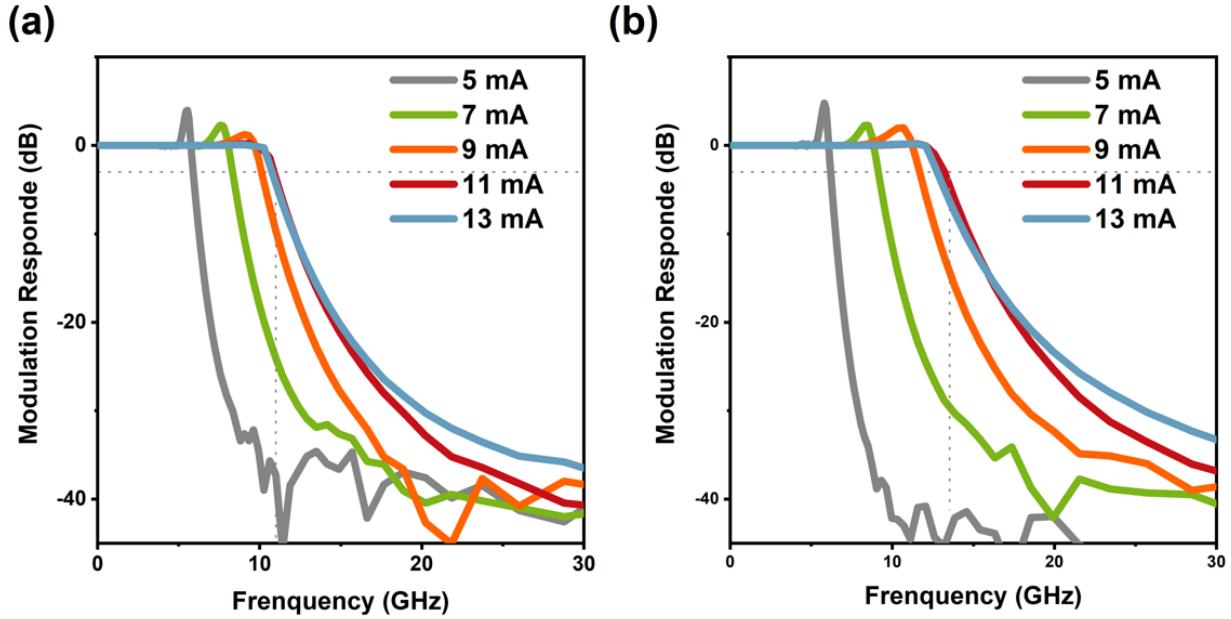


Figure 6.13 Dynamic modulation characteristics. Small-signal modulation response (S21) at various bias currents for (a) the baseline Qdash VCSEL and (b) the composition-engineered VCSEL.

The improvement can be understood through the relaxation-oscillation frequency, which scales approximately with the square root of the differential gain and photon density. Because the engineered Qdash structure exhibits a $\sim 16\%$ increase in differential gain, the relaxation-oscillation frequency shifts to higher values. At the same time, stronger carrier confinement reduces gain compression effects and mitigates damping. As a result, the modulation response maintains its roll-off slope over a wider frequency range before reaching the -3 dB point.

It is important to note that the achieved bandwidth values remain within the typical range reported for wafer-fused long-wavelength VCSELs employing similar cavity configurations. Shorter effective cavities or dielectric DBR structures can further reduce photon lifetime and

increase bandwidth beyond 20 GHz in optimized devices. The present study does not aim to maximize bandwidth through cavity redesign; rather, it isolates and quantifies the intrinsic contribution of gain-medium engineering to dynamic performance.

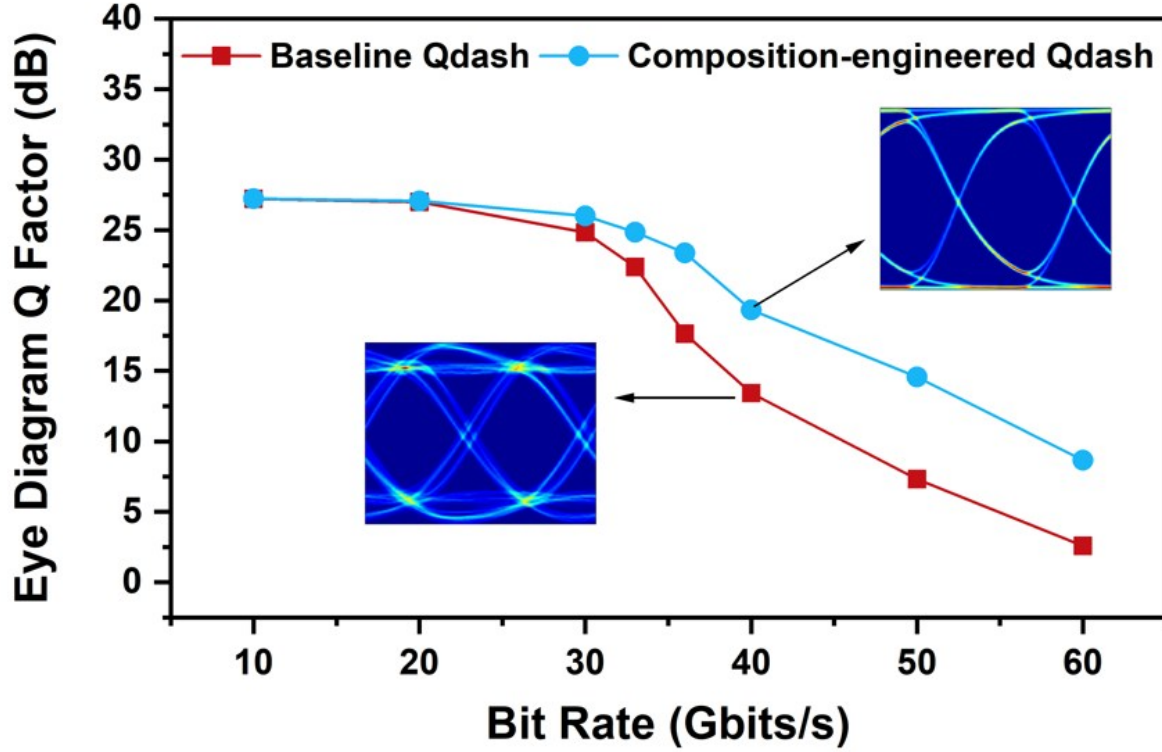


Figure 6.14 Large-signal NRZ eye-diagram Q-factor versus modulation frequency at 11 mA injection current, 10% modulation amplitude. Inserts are eye-diagrams at modulation frequency 40 Gbit/s.

The benefits of the engineered Qdash design become even more apparent under large-signal modulation. Figure 6.7(c) presents non-return-to-zero (NRZ) eye diagrams evaluated at increasing modulation frequencies with a fixed bias current and modulation amplitude. At moderate bit rates, both devices exhibit clear and open eyes. However, as the modulation frequency increases, the baseline device shows progressive eye closure due to limited modulation efficiency and stronger

gain saturation. In contrast, the composition-engineered VCSEL maintains a cleaner eye opening across the tested frequency range.

The improved eye quality is directly related to the enhanced differential gain and reduced nonlinear gain compression. Higher differential gain enables faster carrier–photon coupling, while stronger confinement stabilizes carrier distribution during rapid modulation. Consequently, the engineered structure exhibits improved signal integrity and larger eye-diagram Q factors at high bit rates.

Overall, the dynamic analysis confirms that coordinated bandgap and strain engineering in the Qdash active region leads to measurable improvements in both small-signal and large-signal modulation performance. The results demonstrate that gain-medium optimization provides an effective pathway to enhancing the intrinsic speed of C-band VCSELs, independent of cavity redesign. When combined with advanced cavity engineering and optimized current confinement, the proposed approach offers significant potential for further bandwidth enhancement in future high-speed optical interconnect applications.

6.7 Conclusions

In this chapter, a coordinated bandgap and strain engineering strategy for InAs/InGaAsP quantum-dash active regions in C-band wafer-fused VCSELs has been systematically investigated. Starting from cavity eigenmode analysis, it was shown that increasing Qdash height significantly enhances the optical confinement factor, thereby strengthening the interaction between the cavity mode and the gain medium. However, conventional InAs Qdashes suffer from strong red shifting as height increases, restricting the achievable gain volume for C-band operation.

To overcome this limitation, two complementary engineering approaches were introduced. First, the confinement-layer composition was optimized by selecting an InP first capping layer and

a lower-bandgap 1.10Q InGaAsP second capping layer to improve conduction-band offsets and control strain redistribution. Second, slight phosphorus alloying within the Qdash was employed to increase the intrinsic bandgap and partially relax compressive strain. The combined effect of these modifications enables emission blue-shifting while preserving increased Qdash height and improved carrier confinement.

Electronic-structure analysis revealed that the engineered configuration strengthens electron localization and increases the dipole matrix element associated with the ground-state transition. This enhancement translates into approximately a 16% increase in differential gain compared with the baseline Qdash structure. Device-level simulations confirmed that this intrinsic material improvement leads to an increase in -3 dB modulation bandwidth from 11.2 GHz to 13.4 GHz, as well as improved large-signal eye-diagram quality. Importantly, these gains are achieved without altering the cavity design, demonstrating that gain-medium engineering alone can produce measurable improvements in dynamic performance.

While the present study focuses on physics-based modeling, practical implementation of the proposed design requires careful consideration of fabrication constraints. Precise control of phosphorus incorporation within the Qdash is essential to maintain uniform bandgap modification without introducing excessive compositional fluctuations. The double-capping structure demands high interface quality to prevent defect formation and carrier trapping. Furthermore, strain management across multiple stacked Qdash layers must be optimized to avoid dislocation formation and preserve material quality. Integration with wafer-fused VCSEL platforms also necessitates compatibility with buried tunnel junction processing and mirror bonding procedures. Addressing these technological challenges will be critical for experimental validation of the proposed design concepts.

In summary, this chapter demonstrates that coordinated bandgap and strain engineering provides a physically grounded and practically viable pathway for enhancing the dynamic

performance of C-band Qdash VCSELs. By decoupling emission wavelength from Qdash height, the proposed strategy allows simultaneous optimization of optical confinement and differential gain. Together with the coupling mechanisms discussed in Chapters 4 and 5, these results establish a comprehensive framework for engineering quantum nanostructure gain media tailored to specific device architectures.

Chapter 7 Concluding Remarks

7.1 Summary

This dissertation has presented a comprehensive investigation of quantum-dot and quantum-dash gain materials for Fabry–Pérot lasers and vertical-cavity surface-emitting lasers, with a particular focus on understanding how nanostructure-level physics governs device-level performance. By integrating electronic-structure modeling, optical cavity analysis, and time-domain laser dynamics within a unified framework, this work establishes a coherent pathway linking strain engineering, quantum confinement, carrier transport, and modulation behavior.

A primary contribution of this thesis is the development of an integrated multi-physics simulation framework. Unlike previous approaches in which electronic band-structure modeling and time-domain laser simulations were only loosely connected, the framework presented here explicitly couples optical cavity eigenmode analysis with eight-band $k \cdot p$ calculations and travelling-wave time-domain carrier–photon dynamics. Transition energies, dipole matrix elements, confinement factors, and strain-dependent band offsets are consistently incorporated into the dynamic laser model. Furthermore, additional coupling channels—including vertical stacking effects and lateral interdash tunneling—are embedded directly into the carrier rate equations. This strengthened integration advances the modeling capability toward an electronic design automation-compatible workflow, enabling predictive device-level optimization grounded in microscopic physics.

Building upon this framework, the thesis systematically investigates vertical coupling effects in chirped stacked QD and Qdash structures. It is demonstrated that vertical strain redistribution modifies the transition energy distribution of stacked nanostructures in a manner that depends critically on stacking sequence. While ascending stacking compresses the energy spread,

descending stacking enhances it, thereby broadening the gain bandwidth. This insight transforms vertical coupling from a parasitic effect to a controllable design parameter for broadband semiconductor lasers. The universality of this mechanism is confirmed in both quantum-dot and quantum-dash systems, establishing a general principle for bandwidth engineering through stacking order control.

In addition to vertical coupling, the dissertation examines lateral interdash interactions in dense InAs/InGaAsP Qdash ensembles. A realistic Qdash pair model is constructed to quantify same-shell and heteroshell tunneling processes. It is shown that lateral coupling is dominated by electron tunneling due to lighter effective mass and weaker confinement relative to holes. When incorporated into the time-domain carrier dynamics, this tunneling mechanism enables carrier redistribution from higher-energy to lower-energy Qdashes, reducing threshold current in long-cavity Fabry–Pérot lasers. The analysis further reveals that the impact of lateral coupling is strongly device-dependent, with diminished benefit in small-volume VCSEL configurations where high carrier density and non-radiative recombination dominate threshold behavior. This work clarifies the conditions under which lateral coupling is advantageous and provides guidance for morphology-aware device design.

The final major contribution concerns coordinated bandgap and strain engineering for high-speed C-band Qdash VCSELs. By introducing slight phosphorus alloying within the Qdash and optimizing the double-capping confinement layers, emission wavelength control is decoupled from Qdash height. This strategy enables increased dash volume and improved electron confinement while maintaining C-band operation. The engineered structure exhibits approximately a 16% enhancement in differential gain and a measurable increase in -3 dB modulation bandwidth, accompanied by improved large-signal eye-diagram quality. Importantly, these improvements are achieved without modifying cavity architecture, demonstrating that gain-medium engineering alone can produce substantial dynamic performance enhancement.

Collectively, these contributions define a unified device-level integration strategy based on physics-driven co-design across multiple scales. Strain distribution, quantum confinement, carrier redistribution, and optical cavity parameters are not treated as independent variables but as interconnected elements of a single optimization problem. Vertical and lateral coupling effects are analyzed in conjunction with band alignment and dipole strength, ensuring that nanostructure modifications translate directly into device-level improvements. Through this multiscale integration approach, the thesis establishes a coherent framework for engineering QD/Qdash gain media tailored to broadband, low-threshold, and high-speed semiconductor laser applications.

7.2 Recommendations for Future Work

While this dissertation establishes a comprehensive theoretical framework for understanding and engineering quantum-dot and quantum-dash gain materials, several important research directions remain open. These directions span simulation methodology, emerging device physics, and high-power laser architectures, and together define a natural continuation of the work presented here.

A first priority for future research lies in further development of the integrated multi-physics simulation framework. Although the present model self-consistently combines cavity eigenmode analysis, eight-band $k \cdot p$ electronic-structure calculations, and travelling-wave time-domain laser dynamics, additional physical effects can be incorporated to enhance predictive accuracy. Many-body Coulomb interactions, carrier–carrier scattering, bandgap renormalization, and advanced gain-compression mechanisms may become increasingly important at high injection levels and under high-speed modulation. Similarly, more rigorous electro-thermal coupling models should be integrated to capture self-heating effects and temperature-dependent carrier redistribution under realistic operating conditions. Extending the framework to include parasitic capacitance, resistance, and full electrical circuit modeling would further improve dynamic prediction accuracy for practical devices.

Beyond device-level refinement, integration of the simulation platform into photonic integrated circuit (PIC) design workflows represents an important future direction. In emerging silicon photonics and heterogeneous integration platforms, semiconductor lasers operate not as isolated components but as part of complex systems including modulators, waveguides, filters, and detectors. Embedding the present gain-medium and cavity models into system-level simulators would enable co-optimization of nanostructure design and circuit architecture. Such multiscale simulation capability would bridge the gap between material engineering and functional photonic systems, enabling predictive design of fully integrated optical interconnects.

A second promising direction concerns spin-dynamic quantum-dot and quantum-dash VCSELs. Spin-polarized carrier injection has been shown to modify threshold behavior, polarization dynamics, and modulation speed in short-wavelength VCSELs. Extending this concept to long-wavelength QD/Qdash VCSELs could open new opportunities for ultrafast modulation beyond conventional relaxation-oscillation limits. Incorporating spin-dependent rate equations and spin relaxation mechanisms into the present modelling framework would allow systematic investigation of spin-controlled carrier–photon interactions in nanostructured gain media. Such studies may reveal pathways to achieving enhanced bandwidth, reduced threshold current, and polarization-selective operation in C-band devices.

A third major direction involves high-power quantum-dot and quantum-dash laser architectures. While this dissertation emphasizes broadband and high-speed operation, high-brightness and high-power coherent sources remain essential for applications such as coherent communication, sensing, and lidar. Distributed feedback (DFB) lasers and photonic crystal surface-emitting lasers (PCSELs) incorporating engineered QD/Qdash active regions represent particularly attractive candidates. In these architectures, the interplay between vertical and lateral coupling, strain redistribution, and carrier transport becomes even more critical due to increased thermal loading and modal competition. Applying the coupling and band-engineering principles

developed in this thesis to DFB and PCSEL structures may enable improved spectral purity, power scalability, and thermal robustness.

Finally, experimental validation of the proposed designs constitutes an essential step forward. Precise control of alloy composition, strain distribution, and interface quality will be required to translate simulation-optimized structures into fabricated devices. Close collaboration between epitaxial growth, device fabrication, and modeling efforts will be crucial for refining parameters, calibrating models, and accelerating development cycles. The framework established in this thesis provides a strong foundation for such iterative co-design processes.

In summary, the work presented here opens multiple avenues for extending quantum nanostructure engineering from device-level optimization toward system-level integration and advanced functional concepts. Continued exploration of these directions will further advance the performance, efficiency, and scalability of quantum-dot and quantum-dash semiconductor lasers for next-generation photonic technologies.

Appendix

A.1 Material Parameters Used in the 8-band k-p Model Calculations at RT/LT

Table 1 Material parameters used in the 8-band k-p model calculations at RT/LT.

	Unit	Temp.	InAs	GaP	In _{1-x} Ga _x As _y P _{1-y}
a	Å	RT ¹	6.0583	5.4505	$5.6533xy+6.0583(1-x)y+5.4505x(1-y)+5.8687(1-x)(1-y)$
		LT	6.0584	5.4512	$5.6525xy+6.0584(1-x)y+5.4512x(1-y)+5.8688(1-x)(1-y)$
ρ	kg/m ³	RT/LT	5668	4130	$5317.5xy+5668(1-x)y+4130x(1-y)+4790(1-x)(1-y)$
ϵ_r		RT	14.55	11.1	$13.18xy+14.55(1-x)y+11.1x(1-y)+12.35(1-x)(1-y)$
		LT	14.55	10.86	$12.4xy+14.55(1-x)y+10.86x(1-y)+11.77(1-x)(1-y)$
C_{11}	GPa	RT	83.29	140.5	$119xy+83.29(1-x)y+140.5x(1-y)+101.1(1-x)(1-y)$
		LT	83.3	143.9	$122.3xy+83.3(1-x)y+143.9x(1-y)+102.2(1-x)(1-y)$
C_{12}	GPa	RT	45.26	62.03	$53.8xy+45.26(1-x)y+62.03x(1-y)+56.1(1-x)(1-y)$
		LT	45.3	65.2	$57.1xy+45.3(1-x)y+65.2x(1-y)+57.6(1-x)(1-y)$
C_{44}	GPa	RT	39.59	70.33	$59.4xy+39.59(1-x)y+70.33x(1-y)+44.2(1-x)(1-y)$
		LT	39.6	70.14	$60xy+39.6(1-x)y+70.14x(1-y)+46(1-x)(1-y)$
e_{14}	C/m ²	RT/LT	0.045	0.1	$-0.18(1-y)^2+0.15(1-y)-0.05$
B_{114}	C/m ²	RT/LT	-0.5	-0.7	$-0.4xy-0.5(1-x)y-0.7x(1-y)-1.1(1-x)(1-y)$
B_{124}	C/m ²	RT/LT	-4.1	-2.2	$-3.8xy-4.1(1-x)y-2.2x(1-y)-3.8(1-x)(1-y)$
B_{156}	C/m ²	RT/LT	0.2	-0.7	$-0.7xy+0.2(1-x)y-0.7x(1-y)-0.5(1-x)(1-y)$
m_e	m_0	RT	0.0213	Barrier	$0.0632xy+0.0213(1-x)y+0.158x(1-y)+0.077(1-x)(1-y)$
		LT	0.023	Barrier	$0.0665xy+0.023(1-x)y+0.17x(1-y)+0.08(1-x)(1-y)$
γ_1^L		RT/LT	20.4	Barrier	$7.1xy+20.4(1-x)y+4.04x(1-y)+5.33(1-x)(1-y)$
γ_2^L		RT/LT	8.3	Barrier	$2.02xy+8.3(1-x)y+0.53x(1-y)+1.57(1-x)(1-y)$
γ_3^L		RT/LT	9.1	Barrier	$2.91xy+9.1(1-x)y+1.26x(1-y)+2.11(1-x)(1-y)$
a_c	eV	RT/LT	-10.2	-7.14	$-7.6+1.6x+[0.85xy-1(1-x)y-1.7x(1-y)+0.6(1-x)(1-y)]$
a_v	eV	RT/LT	1	1.7	$-0.85xy+1(1-x)y+1.7x(1-y)-0.6(1-x)(1-y)$
b	eV	RT/LT	-1.8	-1.7	$-1.85xy-1.8(1-x)y-1.7x(1-y)-1.7(1-x)(1-y)$
d	eV	RT/LT	-3.6	-4.4	$-5.1xy-3.6(1-x)y-4.4x(1-y)-4.3(1-x)(1-y)$
		RT	$0.709-0.37y$	$2.43-0.37y$	$0.14(1-y)^2+0.46(1-y)+0.75$
E_c	eV	LT	$0.768-0.37y$	$2.565-0.37y$	$1.423+0.689x-1.185y+0.758x^2+0.18y^2+0.763xy-1.14x^2y-0.845xy^2+0.875x^2y^2$
		RT/LT	$0.35-0.37y$	$-0.33-0.37y$	0
E_v	eV	RT	0.41	0.08	$0.108(1-y)+0.33y-0.06y^2$
Δ	eV	LT	0.38	0.08	$0.341xy+0.38(1-x)y+0.082x(1-y)+0.108(1-x)(1-y)$
E_p	eV	RT/LT	21.5	Barrier	$28.8xy+21.5(1-x)y+31.4x(1-y)+20.7(1-x)(1-y)$

¹ RT = 300 K, LT $\leq$ 10 K based on [143], [144], [145]. However, it is also a good approximation for the LT case when $T = 20$ K due to the negligible difference.

A.2 Main Parameters Used in the TDTW Models for F-P Laser

Table 2 Main parameters used in the TDTW models for F-P Laser

Quantity	Values
Material parameters	
Temperature T	300 K
SCH-WL separation $\Delta E_{\text{SCH-WL}}^e$	5 meV
WL-ES separation $\Delta E_{\text{WL-ES}}^e$	46 meV (10-nm case)
Number of QD groups N	31
Interband transition $\hbar\omega_{i\text{GS1}}$ for $i = (N + 1)/2$	0.801 eV
Interband transition $\hbar\omega_{i\text{GS2}}$ for $i = (N + 1)/2$	0.820 eV
Tunneling time $\tau_{\text{tunneling}}$	1~36 ps
Effective refractive index η	3.5755
Number of QD layers N_l	4 or 5
Qdot surface density N_D	$3 \times 10^{10} \text{ cm}^{-2}$
Qdash surface density N_{Dash}	$2 \times 10^{10} \text{ cm}^{-2}$
Homogeneous linewidth $\hbar\Gamma$	10 meV
Inhomogeneous broadening FWHM ΔE	30 meV
Dipole matrix element d_m for $m = \text{GS1, GS2}$	0.34, 0.36 e·nm
Relaxation time τ_c^m for $m = \text{WL, GS1, GS1}$	3, 3, 3 ps
Spontaneous emission coupling factor β_{sp}	1×10^{-4}
Intrinsic waveguide loss α_i	17 cm ⁻¹
Sample parameters	
Lateral size of the device (QD layer width) W	2.5 μm
Length of sample L	500-1500 μm
Field confinement factor Γ_{xy}	0.06
Power reflectivity r_0^2, r_L^2	0.3, 0.3

A.3 Main Parameters Used in the TDTW Models for VCSEL

Table 3 Main parameters used in the RE & TDTW models for VCSEL

Symbol	Quantity	Values
L	Cavity length	3λ cavity
d_{BTJ}	Diameter of BTJ	5 μm
M	Number of Qdash layers	3×5
ND	Surface density	$2 \times 10^{14} \text{ m}^{-2}$
$\hbar\omega_i$	Transition energies of Qdash	0.802 eV (baseline Qdash) 0.820 eV (composition-engineered Qdash)
Γ	Optical confinement factor	0.02388 (baseline Qdash) 0.02851 (composition-engineered Qdash)
R^{th}	Thermal resistance	$6.4 \times 10^3 \text{ K/W}$
η_i	Quantum efficiency	65%
ΔE	Inhomogeneous broadening	30 meV
L_d	Dipole length	0.693 nm (baseline Qdash) 0.772 nm (composition-engineered Qdash)
T	Ambient temperature	300 K

References

- [1] D. A. B. Miller, “Attojoule Optoelectronics for Low-Energy Information Processing and Communications,” *Journal of Lightwave Technology*, vol. 35, no. 3, pp. 346–396, Feb. 2017, doi: 10.1109/JLT.2017.2647779.
- [2] Y. Lu and H. Gu, “Flexible and Scalable Optical Interconnects for Data Centers: Trends and Challenges,” *IEEE Communications Magazine*, vol. 57, no. 10, pp. 27–33, Oct. 2019, doi: 10.1109/MCOM.001.1900326.
- [3] Y. Li, Y. Zhang, L. Zhang, and A. W. Poon, “Silicon and hybrid silicon photonic devices for intra-datacenter applications: state of the art and perspectives [Invited],” *Photon. Res., PRJ*, vol. 3, no. 5, pp. B10–B27, Oct. 2015, doi: 10.1364/PRJ.3.000B10.
- [4] L. Tao, Y. Ji, J. Liu, A. P. Tao Lau, N. Chi, and C. Lu, “Advanced modulation formats for short reach optical communication systems,” *IEEE Network*, vol. 27, no. 6, pp. 6–13, Nov. 2013, doi: 10.1109/MNET.2013.6678921.
- [5] V. Torres-Company *et al.*, “Laser Frequency Combs for Coherent Optical Communications,” *J. Lightwave Technol., JLT*, vol. 37, no. 7, pp. 1663–1670, Apr. 2019.
- [6] N. Chen *et al.*, “Monolithically integrated four-channel laser array based on high-order surface gratings for O-band CWDM systems,” *Appl. Opt., AO*, vol. 63, no. 17, pp. 4736–4744, Jun. 2024, doi: 10.1364/AO.525280.
- [7] X. Zhang *et al.*, “Telecom-band multiwavelength vertical emitting quantum well nanowire laser arrays,” *Light Sci Appl*, vol. 13, no. 1, p. 230, Sep. 2024, doi: 10.1038/s41377-024-01570-7.
- [8] M. Tan *et al.*, “Co-packaged optics (CPO): status, challenges, and solutions,” *Front. Optoelectron.*, vol. 16, no. 1, p. 1, Mar. 2023, doi: 10.1007/s12200-022-00055-y.
- [9] “Semiconductor Lasers for 3-D Sensing.” Accessed: Jan. 25, 2026. [Online]. Available: https://www.opticaopn.org/home/articles/volume_30/february_2019/features/semic

onductor_lasers_for_3-d_sensing/

[10] J. Ohtsubo, “Semiconductor Lasers and Theory,” in *Semiconductor Lasers: Stability, Instability and Chaos*, J. Ohtsubo, Ed., Cham: Springer International Publishing, 2017, pp. 33–82. doi: 10.1007/978-3-319-56138-7_3.

[11] Z. Xue, Y. Zhu, J. Zeng, M. Pan, and M. Shi, “High-power-efficiency 1.55 μm tapered InP DFB laser for optical communication,” *Optics Communications*, vol. 596, p. 132564, Dec. 2025, doi: 10.1016/j.optcom.2025.132564.

[12] “VCSEL Industry: Communication and Sensing | IEEE eBooks | IEEE Xplore.” Accessed: Apr. 19, 2023. [Online]. Available: <https://ieeexplore.ieee.org/book/9648537>

[13] R. Michalzik, Ed., *VCSELs: Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers*, vol. 166. in Springer Series in Optical Sciences, vol. 166. Berlin, Heidelberg: Springer, 2013. doi: 10.1007/978-3-642-24986-0.

[14] Y. Rao *et al.*, “Long-Wavelength VCSEL Using High-Contrast Grating,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 19, no. 4, pp. 1701311–1701311, Jul. 2013, doi: 10.1109/JSTQE.2013.2246780.

[15] A. Babichev *et al.*, “Long-Wavelength VCSELs: Status and Prospects,” *Photonics*, vol. 10, no. 3, p. 268, Mar. 2023, doi: 10.3390/photonics10030268.

[16] Y. Guo *et al.*, “Hybrid integrated external cavity laser with a 172-nm tuning range,” *APL Photonics*, vol. 7, no. 6, p. 066101, Jun. 2022, doi: 10.1063/5.0088119.

[17] S. Noda, M. Yoshida, T. Inoue, M. De Zoysa, K. Ishizaki, and R. Sakata, “Photonic-crystal surface-emitting lasers,” *Nat Rev Electr Eng*, vol. 1, no. 12, pp. 802–814, Dec. 2024, doi: 10.1038/s44287-024-00113-x.

[18] M. S. Skolnick and D. J. Mowbray, “SELF-ASSEMBLED SEMICONDUCTOR QUANTUM DOTS: Fundamental Physics and Device Applications,” *Annual Review of Materials Research*, vol. 34, no. Volume 34, 2004, pp. 181–218, Aug. 2004, doi: 10.1146/annurev.matsci.34.082103.133534.

- [19] R. J. Hussin and I. B. Karomi, “Progressing in III-V Semiconductor Quantum Dot Lasers Grown Directly on Silicon: A Review,” *Silicon*, vol. 16, no. 15, pp. 5457–5470, Oct. 2024, doi: 10.1007/s12633-024-03098-2.
- [20] J. C. Norman *et al.*, “The Importance of p-Doping for Quantum Dot Laser on Silicon Performance,” *IEEE Journal of Quantum Electronics*, vol. 55, no. 6, pp. 1–11, Dec. 2019, doi: 10.1109/JQE.2019.2941579.
- [21] J. Duan, H. Huang, Z. G. Lu, P. J. Poole, C. Wang, and F. Grillot, “Narrow spectral linewidth in InAs/InP quantum dot distributed feedback lasers,” *Appl. Phys. Lett.*, vol. 112, no. 12, Mar. 2018, doi: 10.1063/1.5022480.
- [22] H. Huang *et al.*, “Epitaxial quantum dot lasers on silicon with high thermal stability and strong resistance to optical feedback,” *APL Photonics*, vol. 5, no. 1, p. 016103, Jan. 2020, doi: 10.1063/1.5120029.
- [23] D. Huang *et al.*, “Feedback Tolerant Quantum Dot Lasers Integrated With 300 mm Silicon Photonics,” *Journal of Lightwave Technology*, vol. 43, no. 4, pp. 1855–1860, Feb. 2025, doi: 10.1109/JLT.2024.3481454.
- [24] J.-Z. Huang *et al.*, “Ultra-broadband flat-top quantum dot comb lasers,” *Photon. Res.*, vol. 10, no. 5, p. 1308, May 2022, doi: 10.1364/PRJ.446349.
- [25] A. Salhi, L. Fortunato, L. Martiradonna, R. Cingolani, M. De Vittorio, and A. Passaseo, “Enhanced modal gain of multilayer InAs/InGaAs/GaAs quantum dot lasers emitting at 1300nm,” *J. Appl. Phys.*, vol. 100, no. 12, p. 123111, Dec. 2006, doi: 10.1063/1.2402744.
- [26] D. Das, H. Ghadi, S. Sengupta, A. Ahmad, A. Manohar, and S. Chakrabarti, “Optimization of the Number of Stacks in the Submonolayer Quantum Dot Heterostructure for Infrared Photodetectors,” *IEEE Transactions on Nanotechnology*, vol. 15, no. 2, pp. 214–219, Mar. 2016, doi: 10.1109/TNANO.2015.2513318.
- [27] A. Sauerwald *et al.*, “Size control of InAs quantum dashes,” *Applied Physics Letters*, vol. 86, no. 25, p. 253112, Jun. 2005, doi: 10.1063/1.1954903.

- [28] N. Sritirawisarn, F. W. M. van Otten, T. J. Eijkemans, and R. Nötzel, “Surface morphology induced InAs quantum dot or dash formation on InGaAsP/InP (1 0 0),” *Journal of Crystal Growth*, vol. 305, no. 1, pp. 63–69, Jul. 2007, doi: 10.1016/j.jcrysgro.2007.04.035.
- [29] S. Wang *et al.*, “High-Power, Narrow-Linewidth, and Low-Noise Quantum Dot Distributed Feedback Lasers,” *Laser & Photonics Reviews*, vol. n/a, no. n/a, p. 2200979, doi: 10.1002/lpor.202200979.
- [30] M. Tadić, F. M. Peeters, K. L. Janssens, M. Korkusiński, and P. Hawrylak, “Strain and band edges in single and coupled cylindrical InAs/GaAs and InP/InGaP self-assembled quantum dots,” *Journal of Applied Physics*, vol. 92, no. 10, pp. 5819–5829, Nov. 2002, doi: 10.1063/1.1510167.
- [31] H. J. Krenner *et al.*, “Direct Observation of Controlled Coupling in an Individual Quantum Dot Molecule,” *Phys. Rev. Lett.*, vol. 94, no. 5, p. 057402, Feb. 2005, doi: 10.1103/PhysRevLett.94.057402.
- [32] W. Tian *et al.*, “Progress in Research on Co-Packaged Optics,” *Micromachines*, vol. 15, no. 10, p. 1211, Oct. 2024, doi: 10.3390/mi15101211.
- [33] Y. Yi and B. Yu, “3D Optoelectronics and Co-Packaged Optics: Innovations, Challenges, and Future Trends,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 32, no. 2: 3-D Horizons in Photonics: Integrated Circuits, pp. 1–15, Mar. 2026, doi: 10.1109/JSTQE.2025.3641790.
- [34] D. Coenen *et al.*, “Thermal Scaling Analysis of Large Hybrid Laser Arrays for Co-Packaged Optics,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 31, no. 2: Pwr. and Effic. Scaling in Semiconductor Lasers, pp. 1–9, Mar. 2025, doi: 10.1109/JSTQE.2024.3444923.
- [35] Y.-T. Yang and C.-M. Hung, “Heterogeneous Integration in Co-Packaged Optics,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 15, no. 3, pp.

427–437, Sep. 2025, doi: 10.1109/JETCAS.2025.3590744.

[36] F. Vallini *et al.*, “Reliability of III-V/Si heterogeneously integrated lasers,” in *Silicon Photonics XX*, SPIE, Mar. 2025, pp. 26–36. doi: 10.1117/12.3043449.

[37] L. Ranno, “Scalable Packaging and Integration Solutions for Next-Generation Photonic Systems,” Thesis, Massachusetts Institute of Technology, 2025. Accessed: Mar. 03, 2026. [Online]. Available: <https://dspace.mit.edu/handle/1721.1/162334>

[38] N. Cheng, D. Ban, and X. Zheng, “Demonstration of a High-Power and High-Reflection- Tolerance Semiconductor Laser for Co-Packaged Optics,” in *Optical Fiber Communication Conference (OFC) 2023 (2023)*, paper M4C.3, Optica Publishing Group, Mar. 2023, p. M4C.3. doi: 10.1364/OFC.2023.M4C.3.

[39] C. Minkenberg, R. Krishnaswamy, A. Zilkie, and D. Nelson, “Co-packaged datacenter optics: Opportunities and challenges,” *IET Optoelectronics*, vol. 15, no. 2, pp. 77–91, 2021, doi: 10.1049/ote2.12020.

[40] B. Buscaino, B. D. Taylor, and J. M. Kahn, “Multi-Tb/s-per-Fiber Coherent Co-Packaged Optical Interfaces for Data Center Switches,” *J. Lightwave Technol., JLT*, vol. 37, no. 13, pp. 3401–3412, Jul. 2019.

[41] B. Buscaino, E. Chen, J. W. Stewart, T. Pham, and J. M. Kahn, “External vs. Integrated Light Sources for Intra-Data Center Co-Packaged Optical Interfaces,” *J. Lightwave Technol., JLT*, vol. 39, no. 7, pp. 1984–1996, Apr. 2021.

[42] K. Papatryfonos *et al.*, “Co-Package Technology Platform for Low-Power and Low-Cost Data Centers,” *Applied Sciences*, vol. 11, no. 13, p. 6098, Jan. 2021, doi: 10.3390/app11136098.

[43] P. Maniotis and D. M. Kuchta, “Exploring the benefits of using co-packaged optics in data center and AI supercomputer networks: a simulation-based analysis [Invited],” *J. Opt. Commun. Netw., JOCN*, vol. 16, no. 2, pp. A143–A156, Feb. 2024, doi: 10.1364/JOCN.501427.

[44] G. Chen, G. Wang, Z. Wang, and L. Wang, “Electronic Chip Package and Co-

Packaged Optics (CPO) Technology for Modern AI Era: A Review,” *Micromachines*, vol. 16, no. 4, p. 431, Apr. 2025, doi: 10.3390/mi16040431.

[45] H. Huang, O. Alkhazragi, D. Liang, and F. Grillot, “Future roles of solid-state quantum dot light sources,” *Appl. Phys. Lett.*, vol. 126, no. 8, p. 080501, Feb. 2025, doi: 10.1063/5.0251447.

[46] G. Kurczveil, D. Liang, M. Fiorentino, and R. G. Beausoleil, “Robust hybrid quantum dot laser for integrated silicon photonics,” *Opt. Express, OE*, vol. 24, no. 14, pp. 16167–16174, Jul. 2016, doi: 10.1364/OE.24.016167.

[47] “What is dense wavelength-division multiplexing (DWDM) and how does it scale bandwidth?,” Search Networking. Accessed: Mar. 04, 2026. [Online]. Available: <https://www.techtarget.com/searchnetworking/definition/dense-wavelength-division-multiplexing-DWDM>

[48] M. Dumont, S. Liu, M. J. Kennedy, and J. Bowers, “High-Efficiency Quantum Dot Lasers as Comb Sources for DWDM Applications,” *Applied Sciences*, vol. 12, no. 4, p. 1836, Jan. 2022, doi: 10.3390/app12041836.

[49] J. N. Kemal *et al.*, “Coherent WDM transmission using quantum-dash mode-locked laser diodes as multi-wavelength source and local oscillator,” *Opt. Express, OE*, vol. 27, no. 22, pp. 31164–31175, Oct. 2019, doi: 10.1364/OE.27.031164.

[50] P. Marin-Palomo *et al.*, “Comb-based WDM transmission at 10 Tbit/s using a DC-driven quantum-dash mode-locked laser diode,” *Opt. Express, OE*, vol. 27, no. 22, pp. 31110–31129, Oct. 2019, doi: 10.1364/OE.27.031110.

[51] S. Zhao *et al.*, “Broadband amplitude squeezing at room temperature in electrically driven quantum dot lasers,” *Phys. Rev. Res.*, vol. 6, no. 3, p. L032021, Jul. 2024, doi: 10.1103/PhysRevResearch.6.L032021.

[52] B. Dong, M. Dumont, O. Terra, H. Wang, A. Netherton, and J. E. Bowers, “Broadband quantum-dot frequency-modulated comb laser,” *Light Sci Appl*, vol. 12, no. 1, p.

182, Jul. 2023, doi: 10.1038/s41377-023-01225-z.

[53] V. Cao *et al.*, “A novel bidirectionally operated chirped quantum-dot based semiconductor optical amplifier using a dual ground state spectrum,” *APL Photonics*, vol. 9, no. 4, p. 046110, Apr. 2024, doi: 10.1063/5.0194677.

[54] N. Patanasemakul, S. Panyakeow, and S. Kanjanachuchai, “Chirped InGaAs quantum dot molecules for broadband applications,” *Nanoscale Res Lett*, vol. 7, no. 1, p. 207, Apr. 2012, doi: 10.1186/1556-276X-7-207.

[55] I. K. Han *et al.*, “Study of Chirped Quantum Dot Superluminescent Diodes,” *Jpn. J. Appl. Phys.*, vol. 44, no. 7S, p. 5692, Jul. 2005, doi: 10.1143/JJAP.44.5692.

[56] R. Yao, N. Weir, C.-S. Lee, and W. Guo, “Broadband Chirped InAs Quantum-Dot Superluminescent Light-Emitting Diodes With In_xAl_{1-x}As Strain-Reducing Layers,” *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1–7, Jun. 2016, doi: 10.1109/JPHOT.2016.2577595.

[57] G. Liu *et al.*, “Mode-Locking and Noise Characteristics of InAs/InP Quantum Dash/Dot Lasers,” *Journal of Lightwave Technology*, vol. 41, no. 13, pp. 4262–4270, Jul. 2023, doi: 10.1109/JLT.2023.3244777.

[58] P. J. Poole, Z. Lu, J. Liu, P. Barrios, Y. Mao, and G. Liu, “A Performance Comparison Between Quantum Dash and Quantum Well Fabry-Pérot Lasers,” *IEEE Journal of Quantum Electronics*, vol. 57, no. 6, pp. 1–7, Dec. 2021, doi: 10.1109/JQE.2021.3107850.

[59] G. Liu *et al.*, “Monolithic InAs/InP Quantum Dash Mode-Locked Lasers for Millimeter-Wave-Over-Fiber Mobile Fronthaul Systems,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 6: Photonic Signal Processing, pp. 1–10, Nov. 2023, doi: 10.1109/JSTQE.2023.3273539.

[60] V. Pejović *et al.*, “Infrared Colloidal Quantum Dot Image Sensors,” *IEEE Transactions on Electron Devices*, vol. 69, no. 6, pp. 2840–2850, Jun. 2022, doi: 10.1109/TED.2021.3133191.

[61] Z. Yue *et al.*, “Quantum-Dot-Based Photoelectrochemical Sensors for Chemical and

Biological Detection,” *ACS Appl. Mater. Interfaces*, vol. 5, no. 8, pp. 2800–2814, Apr. 2013, doi: 10.1021/am3028662.

[62] Yu. M. Shernyakov *et al.*, “Effect of the Active Region and Waveguide Design on the Performance of Edge-Emitting Lasers Based on InGaAs/GaAs Quantum Well-Dots,” *Semiconductors*, vol. 55, no. 3, pp. 333–340, Mar. 2021, doi: 10.1134/S1063782621030167.

[63] L. Deng, L. Han, Y. Xi, X. Li, and W.-P. Huang, “Design Optimization for High-Performance Self-Assembled Quantum Dot Lasers With Fabry–Perot Cavity,” *IEEE Photonics Journal*, vol. 4, no. 5, pp. 1600–1609, Oct. 2012, doi: 10.1109/JPHOT.2012.2211003.

[64] V. Khatri, V. Sichkovskyi, L. Popilevsky, Y. Kauffmann, G. Eisenstein, and J. P. Reithmaier, “Increased Modal Gain in 1.55 μm Quantum Dot Lasers Based on Improved Size Homogeneity Obtained by Comprehensive Growth Optimization,” *ACS Photonics*, vol. 12, no. 7, pp. 3687–3697, Jul. 2025, doi: 10.1021/acsp Photonics.5c00616.

[65] M. Yang *et al.*, “Optimization design for high-quality factor 1.3 μm InAs/InGaAs quantum dot square microcavity lasers on silicon with output waveguide structures,” *Appl. Phys. A*, vol. 125, no. 8, p. 578, Aug. 2019, doi: 10.1007/s00339-019-2875-3.

[66] Y. Mao *et al.*, “Ultralow Noise and Timing Jitter Semiconductor Quantum-Dot Passively Mode-Locked Laser for Terabit/s Optical Networks,” *Photonics*, vol. 9, no. 10, p. 695, Oct. 2022, doi: 10.3390/photonics9100695.

[67] S. Wang *et al.*, “High-Power, Narrow-Linewidth, and Low-Noise Quantum Dot Distributed Feedback Lasers,” *Laser & Photonics Reviews*, vol. 17, no. 9, p. 2200979, 2023, doi: 10.1002/lpor.202200979.

[68] J. Duan, X.-G. Wang, Y.-G. Zhou, C. Wang, and F. Grillot, “Carrier-Noise-Enhanced Relative Intensity Noise of Quantum Dot Lasers,” *IEEE Journal of Quantum Electronics*, vol. 54, no. 6, pp. 1–7, Dec. 2018, doi: 10.1109/JQE.2018.2880452.

[69] T. Habruseva, D. Arsenijević, M. Kleinert, D. Bimberg, G. Huyet, and S. P. Hegarty, “Optimum phase noise reduction and repetition rate tuning in quantum-dot mode-locked

lasers,” *Appl. Phys. Lett.*, vol. 104, no. 2, p. 021112, Jan. 2014, doi: 10.1063/1.4861604.

[70] J. C. Norman, D. Jung, Y. Wan, and J. E. Bowers, “Perspective: The future of quantum dot photonic integrated circuits,” *APL Photonics*, vol. 3, no. 3, p. 030901, Mar. 2018, doi: 10.1063/1.5021345.

[71] C. Shang *et al.*, “Perspectives on Advances in Quantum Dot Lasers and Integration with Si Photonic Integrated Circuits,” *ACS Photonics*, vol. 8, no. 9, pp. 2555–2566, Sep. 2021, doi: 10.1021/acsp Photonics.1c00707.

[72] S. Banyoudeh, A. Abdollahinia, V. Sichkovskiy, and J. P. Reithmaier, “1.5- μ m quantum dot laser material with high temperature stability of threshold current density and external differential efficiency,” in *Novel In-Plane Semiconductor Lasers XV*, SPIE, Mar. 2016, pp. 68–74. doi: 10.1117/12.2209085.

[73] Z. Lv *et al.*, “Ultra-high thermal stability InAs/GaAs quantum dot lasers grown on on-axis Si (001) with a record-high continuous-wave operating temperature of 150 °C,” *Opt. Express, OE*, vol. 31, no. 15, pp. 24173–24182, Jul. 2023, doi: 10.1364/OE.494251.

[74] Y. Arakawa, “Progress and prospect of quantum dot lasers,” in *Optoelectronics, Materials, and Devices for Communications*, SPIE, Oct. 2001, pp. 179–185. doi: 10.1117/12.444959.

[75] Ph. Lelong, K. Suzuki, G. Bastard, H. Sakaki, and Y. Arakawa, “Enhancement of the Coulomb correlations in type-II quantum dots,” *Physica E: Low-dimensional Systems and Nanostructures*, vol. 7, no. 3, pp. 393–397, May 2000, doi: 10.1016/S1386-9477(99)00348-3.

[76] Y. Wan *et al.*, “Low Dark Current 1.55 Micrometer InAs Quantum Dash Waveguide Photodiodes,” *ACS Nano*, vol. 14, no. 3, pp. 3519–3527, Mar. 2020, doi: 10.1021/acsnano.9b09715.

[77] A. J. Zilkie *et al.*, “Carrier Dynamics of Quantum-Dot, Quantum-Dash, and Quantum-Well Semiconductor Optical Amplifiers Operating at 1.55 μ m,” *IEEE Journal of Quantum Electronics*, vol. 43, no. 11, pp. 982–991, Nov. 2007, doi:

10.1109/JQE.2007.904474.

[78] J. C. Norman *et al.*, “A Review of High-Performance Quantum Dot Lasers on Silicon,” *IEEE Journal of Quantum Electronics*, vol. 55, no. 2, pp. 1–11, Apr. 2019, doi: 10.1109/JQE.2019.2901508.

[79] F. Grillot, Bé. Dagens, J.-G. Provost, H. Su, and L. F. Lester, “Gain Compression and Above-Threshold Linewidth Enhancement Factor in $1.3\text{-}\mu\text{m}$ InAs–GaAs Quantum-Dot Lasers,” *IEEE Journal of Quantum Electronics*, vol. 44, no. 10, pp. 946–951, Oct. 2008, doi: 10.1109/JQE.2008.2003106.

[80] N. N. Ledentsov *et al.*, “High Speed VCSEL Technology and Applications,” *J. Lightwave Technol.*, *JLT*, vol. 40, no. 6, pp. 1749–1763, Mar. 2022.

[81] N. Ledentsov *et al.*, “Quantum dot 850 nm VCSELs with extreme high temperature stability operating at bit rates up to 25 Gbit/s at 150 °C,” *Solid-State Electronics*, vol. 155, pp. 150–158, May 2019, doi: 10.1016/j.sse.2019.03.018.

[82] S. A. Blokhin *et al.*, “High Power Single Mode 1300-nm Superlattice Based VCSEL: Impact of the Buried Tunnel Junction Diameter on Performance,” *IEEE Journal of Quantum Electronics*, vol. 58, no. 2, pp. 1–15, Apr. 2022, doi: 10.1109/JQE.2022.3141418.

[83] A. Babichev *et al.*, “Long-Wavelength VCSELs: Status and Prospects,” *Photonics*, vol. 10, no. 3, Art. no. 3, Mar. 2023, doi: 10.3390/photonics10030268.

[84] K. O. Voropaev, B. I. Seleznev, A. Y. Prokhorov, A. S. Ionov, and S. A. Blokhin, “The fabrication technology of VCSELs emitting in the 1.55 μm waveband,” *J. Phys.: Conf. Ser.*, vol. 1658, no. 1, p. 012069, Oct. 2020, doi: 10.1088/1742-6596/1658/1/012069.

[85] S. Spiga *et al.*, “Single-Mode High-Speed 1.5- μm VCSELs,” *Journal of Lightwave Technology*, vol. 35, no. 4, pp. 727–733, Feb. 2017, doi: 10.1109/JLT.2016.2597870.

[86] A. V. Babichev *et al.*, “Vertical-Cavity Surface-Emitting 1.55- μm Lasers Fabricated by Fusion,” *Tech. Phys. Lett.*, vol. 44, no. 1, pp. 24–27, Jan. 2018, doi: 10.1134/S1063785018010029.

- [87] S. A. Blokhin *et al.*, “1550 nm Range High-Speed Single-Mode Vertical-Cavity Surface-Emitting Lasers,” *Semiconductors*, vol. 57, no. 4, pp. 221–230, Apr. 2023, doi: 10.1134/S1063782623070072.
- [88] C. J. Chang-Hasnain, Y. Zhou, M. C. Y. Huang, and C. Chase, “High-Contrast Grating VCSELs,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 15, no. 3, pp. 869–878, May 2009, doi: 10.1109/JSTQE.2009.2015195.
- [89] S. A. Blokhin *et al.*, “High-Speed Vertical-Cavity Surface-Emitting 1550-nm-Range Lasers Manufactured by the Wafer Fusion Technology,” *Bull. Lebedev Phys. Inst.*, vol. 50, no. 2, pp. S140–S147, Aug. 2023, doi: 10.3103/S1068335623140026.
- [90] Y. Arakawa and H. Sakaki, “Multidimensional quantum well laser and temperature dependence of its threshold current,” *Appl. Phys. Lett.*, vol. 40, no. 11, pp. 939–941, Jun. 1982, doi: 10.1063/1.92959.
- [91] N. N. Ledentsov, V. M. Ustinov, V. A. Shchukin, P. S. Kop’ev, Zh. I. Alferov, and D. Bimberg, “Quantum dot heterostructures: Fabrication, properties, lasers (Review),” *Semiconductors*, vol. 32, no. 4, pp. 343–365, Apr. 1998, doi: 10.1134/1.1187396.
- [92] P. Blood, *Quantum Confined Laser Devices: Optical gain and recombination in semiconductors*. OUP Oxford, 2015.
- [93] C. Pryor, “Eight-band calculations of strained InAs/GaAs quantum dots compared with one-, four-, and six-band approximations,” *Phys. Rev. B*, vol. 57, no. 12, pp. 7190–7195, Mar. 1998, doi: 10.1103/PhysRevB.57.7190.
- [94] P. Kaczmarkiewicz and P. Machnikowski, “Electronic and optical properties of non-uniformly shaped InAs/InP quantum dashes,” *Semicond. Sci. Technol.*, vol. 27, no. 10, p. 105012, Aug. 2012, doi: 10.1088/0268-1242/27/10/105012.
- [95] P. Goyal, S. Gupta, G. Kaur, and B. K. Kaushik, “Performance analysis of VCSEL using finite difference time domain method,” *Optik*, vol. 156, pp. 505–513, Mar. 2018, doi: 10.1016/j.ijleo.2017.11.201.

- [96] J. H. (Eric) Kim, L. Chrostowski, E. Bisailon, and D. V. Plant, “DBR, Sub-wavelength grating, and Photonic crystal slab Fabry-Perot cavity design using phase analysis by FDTD,” *Opt. Express, OE*, vol. 15, no. 16, pp. 10330–10339, Aug. 2007, doi: 10.1364/OE.15.010330.
- [97] M. Rossetti, P. Bardella, and I. Montrosset, “Modeling Passive Mode-Locking in Quantum Dot Lasers: A Comparison Between a Finite-Difference Traveling-Wave Model and a Delayed Differential Equation Approach,” *IEEE Journal of Quantum Electronics*, vol. 47, no. 5, pp. 569–576, May 2011, doi: 10.1109/JQE.2010.2104135.
- [98] A. E. Abouelez, E. Eldiwany, M. B. El Mashade, and H. A. Konber, “TIME-DOMAIN TRAVELLING-WAVE MODEL FOR QUANTUM DOT BASED VERTICAL CAVITY LASER DEVICES,” *PIER M*, vol. 65, pp. 29–42, 2018, doi: 10.2528/PIERM17112103.
- [99] M. Gioannini and M. Rossetti, “Time-Domain Traveling Wave Model of Quantum Dot DFB Lasers,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 17, no. 5, pp. 1318–1326, Sep. 2011, doi: 10.1109/JSTQE.2011.2128857.
- [100] M. Z. M. Khan, T. K. Ng, and B. S. Ooi, “Self-assembled InAs/InP quantum dots and quantum dashes: Material structures and devices,” *Progress in Quantum Electronics*, vol. 38, no. 6, pp. 237–313, Nov. 2014, doi: 10.1016/j.pquantelec.2014.11.001.
- [101] Y. Xiong and X. Zhang, “InAs/InP quantum dots stacking: Impact of spacer layer on optical properties,” *Journal of Applied Physics*, vol. 125, no. 9, p. 093103, Mar. 2019, doi: 10.1063/1.5082722.
- [102] Z. Yao *et al.*, “Recent Developments of Quantum Dot Materials for High Speed and Ultrafast Lasers,” *Nanomaterials*, vol. 12, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/nano12071058.
- [103] X. Yu *et al.*, “Optically enhanced single- and multi-stacked 1.55 μm InAs/InAlGaAs/InP quantum dots for laser applications,” *J. Phys. D: Appl. Phys.*, vol. 56, no.

28, p. 285101, Apr. 2023, doi: 10.1088/1361-6463/acc875.

[104] J. H. Oh, K. J. Chang, G. Ihm, and S. J. Lee, “Electronic structure and optical properties of coupled quantum dots,” *Phys. Rev. B*, vol. 53, no. 20, pp. R13264–R13267, May 1996, doi: 10.1103/PhysRevB.53.R13264.

[105] P. Holewa *et al.*, “Interdash Coupling within Dense Ensembles of Quantum Dashes: Comparison of In As / (In , Al , Ga) As / In P and In As / (In , Al) As / In P Systems,” *Phys. Rev. Applied*, vol. 17, no. 5, p. 054028, May 2022, doi: 10.1103/PhysRevApplied.17.054028.

[106] C. Cornet *et al.*, “Increase of charge-carrier redistribution efficiency in a laterally organized superlattice of coupled quantum dots,” *Phys. Rev. B*, vol. 74, no. 24, p. 245315, Dec. 2006, doi: 10.1103/PhysRevB.74.245315.

[107] G. Chen and X. Zhang, “The lateral coupling effect in InAs/InGaAsP/InP quantum dash,” *Journal of Applied Physics*, vol. 138, no. 1, p. 013102, Jul. 2025, doi: 10.1063/5.0279263.

[108] R. Gourishetty, S. R. Shriram, D. P. Panda, and S. Chakrabarti, “Analytical Model and Experimental Analysis to Estimate the Interdiffusion and Optoelectronic Properties of Coupled InAs Quantum Dots Post Rapid Thermal Processing,” *IEEE Transactions on Electron Devices*, vol. 69, no. 7, pp. 3775–3782, Jul. 2022, doi: 10.1109/TED.2022.3175683.

[109] M. Zieliński, “Valence band offset, strain and shape effects on confined states in self-assembled InAs/InP and InAs/GaAs quantum dots,” *J. Phys.: Condens. Matter*, vol. 25, no. 46, p. 465301, Oct. 2013, doi: 10.1088/0953-8984/25/46/465301.

[110] Y. Xiong and X. Zhang, “Two-state lasing at room temperature in InAs/InP quantum dots,” *Journal of Applied Physics*, vol. 126, no. 13, p. 133102, Oct. 2019, doi: 10.1063/1.5110316.

[111] M. A. Herman and H. Sitter, *Molecular Beam Epitaxy: Fundamentals and Current Status*. Springer Science & Business Media, 2012.

[112]C. Pryor, J. Kim, L. W. Wang, A. J. Williamson, and A. Zunger, “Comparison of two methods for describing the strain profiles in quantum dots,” *J. Appl. Phys.*, vol. 83, no. 5, pp. 2548–2554, Mar. 1998, doi: 10.1063/1.366631.

[113]H. Ilatikhameneh, T. A. Ameen, G. Klimeck, and R. Rahman, “Universal Behavior of Atomistic Strain in Self-Assembled Quantum Dots,” *IEEE Journal of Quantum Electronics*, vol. 52, no. 7, pp. 1–8, Jul. 2016, doi: 10.1109/JQE.2016.2573959.

[114]M. Zieliński, “Valence band offset, strain and shape effects on confined states in self-assembled InAs/InP and InAs/GaAs quantum dots,” *J. Phys.: Condens. Matter*, vol. 25, no. 46, p. 465301, Oct. 2013, doi: 10.1088/0953-8984/25/46/465301.

[115]C.-Y. Wang, M. Denda, and E. Pan, “Analysis of quantum-dot-induced strain and electric fields in piezoelectric semiconductors of general anisotropy,” *International Journal of Solids and Structures*, vol. 43, no. 25, pp. 7593–7608, Dec. 2006, doi: 10.1016/j.ijsolstr.2006.03.019.

[116]A. D. Andreev, J. R. Downes, D. A. Faux, and E. P. O’Reilly, “Strain distributions in quantum dots of arbitrary shape,” *J. Appl. Phys.*, vol. 86, no. 1, pp. 297–305, Jul. 1999, doi: 10.1063/1.370728.

[117]O. Stier, M. Grundmann, and D. Bimberg, “Electronic and optical properties of strained quantum dots modeled by 8-band k-p theory,” *Phys. Rev. B*, vol. 59, no. 8, pp. 5688–5701, Feb. 1999, doi: 10.1103/PhysRevB.59.5688.

[118]M. Grundmann, O. Stier, and D. Bimberg, “InAs/GaAs pyramidal quantum dots: Strain distribution, optical phonons, and electronic structure,” *Phys. Rev. B*, vol. 52, no. 16, pp. 11969–11981, Oct. 1995, doi: 10.1103/PhysRevB.52.11969.

[119]G. Bester and A. Zunger, “Cylindrically shaped zinc-blende semiconductor quantum dots do not have cylindrical symmetry: Atomistic symmetry, atomic relaxation, and piezoelectric effects,” *Phys. Rev. B*, vol. 71, no. 4, p. 045318, Jan. 2005, doi: 10.1103/PhysRevB.71.045318.

- [120] G. Bester, X. Wu, D. Vanderbilt, and A. Zunger, “Importance of Second-Order Piezoelectric Effects in Zinc-Blende Semiconductors,” *Phys. Rev. Lett.*, vol. 96, no. 18, p. 187602, May 2006, doi: 10.1103/PhysRevLett.96.187602.
- [121] A. Schliwa, M. Winkelkemper, and D. Bimberg, “Impact of size, shape, and composition on piezoelectric effects and electronic properties of In(Ga)As/GaAs quantum dots,” *Phys. Rev. B*, vol. 76, no. 20, p. 205324, Nov. 2007, doi: 10.1103/PhysRevB.76.205324.
- [122] M. Zieliński, M. Korkusiński, and P. Hawrylak, “Atomistic tight-binding theory of multiexciton complexes in a self-assembled InAs quantum dot,” *Phys. Rev. B*, vol. 81, no. 8, p. 085301, Feb. 2010, doi: 10.1103/PhysRevB.81.085301.
- [123] S. Lee, O. L. Lazarenkova, P. von Allmen, F. Oyafuso, and G. Klimeck, “Effect of wetting layers on the strain and electronic structure of InAs self-assembled quantum dots,” *Phys. Rev. B*, vol. 70, no. 12, p. 125307, Sep. 2004, doi: 10.1103/PhysRevB.70.125307.
- [124] G. Bester, “Electronic excitations in nanostructures: an empirical pseudopotential based approach,” *J. Phys.: Condens. Matter*, vol. 21, no. 2, p. 023202, Dec. 2008, doi: 10.1088/0953-8984/21/2/023202.
- [125] J. Even, F. Doré, C. Cornet, and L. Pedesseau, “Semianalytical model for simulation of electronic properties of narrow-gap strained semiconductor quantum nanostructures,” *Phys. Rev. B*, vol. 77, no. 8, p. 085305, Feb. 2008, doi: 10.1103/PhysRevB.77.085305.
- [126] J. Saha, D. Panda, D. Das, V. Chavan, and S. Chakrabarti, “Enhanced luminescence and optical performance through strain minimization in self-assembled InAs QDs using dual quaternary-ternary/ternary-quaternary capping,” *Journal of Luminescence*, vol. 197, pp. 297–303, May 2018, doi: 10.1016/j.jlumin.2018.01.010.
- [127] L. A. Coldren, S. W. Corzine, and M. L. Mashanovitch, *Diode Lasers and Photonic Integrated Circuits*. John Wiley & Sons, 2012.
- [128] A. Lanacer, N. Shtinkov, P. Desjardins, R. A. Masut, and R. Leonelli, “Optical

emission from InAs/InP self-assembled quantum dots: evidence for As/P intermixing,” *Semicond. Sci. Technol.*, vol. 22, no. 12, p. 1282, Nov. 2007, doi: 10.1088/0268-1242/22/12/007.

[129] L. A. Coldren, S. W. Corzine, and M. L. Mashanovitch, *Diode Lasers and Photonic Integrated Circuits*. John Wiley & Sons, 2012.

[130] Y. XIONG, “Modeling of Self-Assembled Quantum Dot Lasers,” phd, Concordia University, 2019. Accessed: Dec. 27, 2022. [Online]. Available: <https://spectrum.library.concordia.ca/id/eprint/986062/>

[131] R. J. Luyken, A. Lorke, A. O. Govorov, J. P. Kotthaus, G. Medeiros-Ribeiro, and P. M. Petroff, “The dynamics of tunneling into self-assembled InAs dots,” *Applied Physics Letters*, vol. 74, no. 17, pp. 2486–2488, Apr. 1999, doi: 10.1063/1.123015.

[132] S. L. Chuang and N. Holonyak Jr., “Efficient quantum well to quantum dot tunneling: Analytical solutions,” *Applied Physics Letters*, vol. 80, no. 7, pp. 1270–1272, Feb. 2002, doi: 10.1063/1.1449535.

[133] Z. Jiao, R. Zhang, X. Zhang, J. Liu, and Z. Lu, “Modeling of Single-Section Quantum Dot Mode-Locked Lasers: Impact of Group Velocity Dispersion and Self Phase Modulation,” *IEEE Journal of Quantum Electronics*, vol. 49, no. 12, pp. 1008–1015, Dec. 2013, doi: 10.1109/JQE.2013.2285115.

[134] S. F. Yu, “An improved time-domain traveling-wave model for vertical-cavity surface-emitting lasers,” *IEEE Journal of Quantum Electronics*, vol. 34, no. 10, pp. 1938–1948, Oct. 1998, doi: 10.1109/3.720230.

[135] G. Liu *et al.*, “InAs/InP quantum dot mode-locked laser with an aggregate 12.544 Tbit/s transmission capacity,” *Opt. Express, OE*, vol. 30, no. 3, pp. 3205–3214, Jan. 2022, doi: 10.1364/OE.441820.

[136] Z. G. Lu, J. R. Liu, S. Raymond, P. J. Poole, P. J. Barrios, and D. Poitras, “312-fs pulse generation from a passive C-band InAs/InP quantum dot mode-locked laser,” *Opt.*

Express, OE, vol. 16, no. 14, pp. 10835–10840, Jul. 2008, doi: 10.1364/OE.16.010835.

[137] J. Liu, Z. Lu, S. Raymond, P. J. Poole, P. J. Barrios, and D. Poitras, “Dual-wavelength 92.5 GHz self-mode-locked InP-based quantum dot laser,” *Opt. Lett., OL*, vol. 33, no. 15, pp. 1702–1704, Aug. 2008, doi: 10.1364/OL.33.001702.

[138] “Shriram et al_2022_Quaternary – alloyed capping for strain and band engineering in InAs sub –.pdf.”

[139] S. R. Shriram *et al.*, “The role and growth of strain – reducing layer by molecular -beam epitaxy in a multi – stack InAs/(In,Ga)As sub - monolayer quantum dot heterostructure,” *Optical Materials*, vol. 114, p. 110817, Apr. 2021, doi: 10.1016/j.optmat.2021.110817.

[140] R.-J. K. Obhi *et al.*, “Indium arsenide single quantum dash morphology and composition for wavelength tuning in quantum dash lasers,” *Applied Physics Letters*, vol. 122, no. 5, p. 051104, Jan. 2023, doi: 10.1063/5.0133657.

[141] Y. Xiong and X. Zhang, “Wavelength Blue-Shifting and Gain Spectral Bandwidth of InAs/InP Quantum Dots for Laser Applications Around $1.55\ \mu\text{m}$,” *IEEE Journal of Quantum Electronics*, vol. 54, no. 1, pp. 1–9, Feb. 2018, doi: 10.1109/JQE.2017.2779880.

[142] A. Somers, W. Kaiser, J. P. Reithmaier, A. Forchel, M. Gioannini, and I. Montrosset, “Optical gain properties of InAs/InAlGaAs/InP quantum dash structures with a spectral gain bandwidth of more than 300nm,” *Appl. Phys. Lett.*, vol. 89, no. 6, p. 061107, Aug. 2006, doi: 10.1063/1.2266994.

[143] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, “Band parameters for III–V compound semiconductors and their alloys,” *Journal of Applied Physics*, vol. 89, no. 11, pp. 5815–5875, Jun. 2001, doi: 10.1063/1.1368156.

[144] W. Ouerghui, A. Melliti, M. A. Maaref, and J. Bloch, “Dependence on temperature of homogeneous broadening of InGaAs/InAs/GaAs quantum dot fundamental transitions,” *Physica E: Low-dimensional Systems and Nanostructures*, vol. 28, no. 4, pp. 519–

524, Sep. 2005, doi: 10.1016/j.physe.2005.05.051.

[145] Y. Xiong and X. Zhang, “An Accurate Method of Modeling Self-Assembled InAs/InGaAsP/InP (001) Quantum Dot With Double-Capping Procedure,” *IEEE Journal of Quantum Electronics*, vol. 53, no. 6, pp. 1–11, Dec. 2017, doi: 10.1109/JQE.2017.2762400.

Publications

- [1] **G. Chen**, F. Huang, and X. Zhang, “Vertical Coupling Effect on Gain Bandwidth of Chirped InAs/InP Quantum Dot Structures,” *IEEE Journal of Quantum Electronics*, vol. 60, no. 2, pp. 1–9, Apr. 2024, doi: 10.1109/JQE.2024.3357031.
- [2] **G. Chen** and X. Zhang, “The lateral coupling effect in InAs/InGaAsP/InP quantum dash,” *Journal of Applied Physics*, vol. 138, no. 1, p. 013102, July 2025, doi: 10.1063/5.0279263.
- [3] **G. Chen** and X. Zhang, “Bandwidth Broadening from Vertical Strain Coupling Effect in Chirped Stacked InAs/InGaAsP Quantum Dash Lasers,” in *2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, June 2023, pp. 1–1. doi: 10.1109/CLEO/Europe-EQEC57999.2023.10232021.
- [4] **G. Chen**, W. Yang, and X. Zhang, “Composition-engineered quantum dashes for high-speed C-band VCSELs,” *J. Appl. Phys.*, vol. 139, no. 13, Apr. 2026, doi: 10.1063/5.0316849.
- [5] F. Huang, **G. Chen**, and X. Zhang, “Modeling Electronic and Optical Properties of InAs/InP Quantum Dots,” *Photonics*, vol. 11, no. 8, Art. no. 8, Aug. 2024, doi: 10.3390/photonics11080749.