Design and analysis of antiresonant reflecting optical waveguide vertical cavity surface emitting lasers and amplifiers

Chen, Nanshu

2009

Chen, N. (2009). Design and analysis of antiresonant reflecting optical waveguide vertical cavity surface emitting lasers and amplifiers. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/15160>

<https://doi.org/10.32657/10356/15160>

DESIGN AND ANALYSIS OF ANTIRESONANT REFLECTING OPTICAL WAVEGUIDE VERTICAL CAVITY SURFACE EMITTING LASERS AND AMPLIFIERS

CHEN NANSHU

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2009

Acknowledgements

First of all, I would like to thank my supervisor, Prof. Yu Siu Fung for giving me the opportunity to carry out this research under his guidance. His continuous support and encouragement during these years are invaluable to my study and research. His deep knowledge, enthusiasm and rigorous attitude to research and teaching have greatly impressed me and influenced me, and will definitely benefit me a lot in my future study and career.

I am also very thankful to my research group members, Clement Yuen, Eunice Leong, Abiyasa and Li Hongdong. They are always willing to help and I am always learning new things through the discussions with them. We are from different countries with different cultures, but we have still built good friendship that I will cherish all the time.

My thanks also go to all former and current members of Photonics Research Centre (PhRC) and Nanoelectronics Lab of NTU. I am always receiving their help, advice and encouragement during these years.

Last but not least, I would like to thank my beloved family and all my friends. You are the source of my strength and everything is possible because of you.

Contents

Acknowledgements.....	i
Summary	v
List of Figures	vii
List of Tables	xiii
1. Introduction.....	1
1.1 Motivation.....	1
1.2 Objective	5
1.3 Major Contributions of the Thesis	6
1.4 Organization of the Thesis	8
2. Background and Literature Review	13
2.1 Vertical Cavity Surface Emitting Lasers	13
2.2 Confinement configurations of VCSELs	16
2.3 ARROW VCSELs	22
2.4 ARROW VCISOAs.....	23
2.5 Conclusion	26
3. Analysis of the Transverse Leaky Modes of Large-area Antiresonant Reflecting Optical Waveguide Vertical Cavity Surface Emitting Lasers..	29
3.1 Introduction.....	30
3.2 Modeling large-area ARROW VCSELs	32
3.3 Analysis of the transverse leaky modes	42
3.4 Discussion and Conclusion	56
4. Study of ARROW VCSELs under External Optical Feedback	61
4.1 Introduction.....	61

4.2 Numerical Simulations.....	63
4.3 Conclusion	70
5. Suppression of Polarization Switching in Birefringent ARROW VCSELs	73
5.1 Introduction.....	73
5.2 Model	75
5.3 Numerical Simulations.....	77
5.4 Discussion and Conclusion	84
6. Analysis and Design of Large-area Anti-Resonant Reflecting Optical Waveguide Vertical-Cavity Semiconductor Optical Amplifiers	87
6.1 Introduction.....	87
6.2 Theoretical Model	89
6.3 Simulation Results	96
6.4 Conclusions.....	116
7. Discussion and Conclusion	119
Author's Publications.....	123

Summary

In the past two decades, semiconductor optoelectronic devices (i.e. semiconductor lasers and amplifiers, etc) have played important roles in numerous application areas, especially in telecommunication systems. With the rapid growth of telecommunication market, these devices have been attracting great research interests to improve their single-mode high-power characteristics. Vertical cavity surface emitting lasers (VCSELs) and amplifiers (VCSOAs) are of the most promising devices that have been significantly improved the single-mode high-power performance of semiconductor lasers and amplifiers. Higher operating stability is found to be achievable by implementing antiresonant reflecting optical waveguide (ARROW) to VCSELs and VCSOAs.

This doctoral thesis studies the optical characteristics of ARROW VCSELs and VCSOAs through computer modeling and simulation. The main factors (i.e. multi-transverse mode competition, polarization switching, external optical feedback etc.) that may impair the stability of ARROW VCSELs and VCSOAs' high-power single-mode operation are analyzed numerically. Based on these analyses, design optimization methods are proposed to improve the single-mode high-power performance of ARROW VCSELs and VCSOAs.

List of Figures

Figure 1.1 VCSEL shipments statistics and prediction for 2005-2008 (courtesy of CIR)	2
Figure 2.1 Basic structure of an electric-pumped VCSEL	13
Figure 2.2 Schematic of a typical gain-guided VCSEL with ion-implantation.	17
Figure 2.3 Schematic of an index-guided VCSEL with double oxide aperture.	18
Figure 2.4 Schematic of an antiguided VCSEL and the corresponding profile of transverse effective refractive index.....	20
Figure 2.5 Transverse effective refractive index profile of a typical cylindrical ARROW structure and the transverse optical field of the fundamental mode inside it.....	21
Figure 2.6 Two operation modes of VCSEA: transmission mode (left) and reflection mode (right).....	24
Figure 3.1 Schematic of an ARROW VCSEL	32
Figure 3.2 Normalized optical field intensity profile of LM_{01} , LM_{11} , LM_{02} , LM_{12}	34

- Figure 3.3** Steady-state characteristics of a 12- μm -core-diameter ARROW VCSEL. (a) L-I curve, (b) GM, (c) RLM, and (d) SMSR.....45
- Figure 3.4** Steady-state characteristics of a 12- μm -core-diameter ARROW VCSEL. (a) Field-intensity profile of LM_{01}^i , (b) field-intensity of LM_{11}^i , (c) transverse refractive-index change, (d) N_{c0} ($\times 10^{18} \text{ cm}^{-3}$), (e) N_{c2} ($\times 10^{18} \text{ cm}^{-3}$), and (f) temperature rise along the transverse direction in active region (K). The arrows indicate the change in profiles with the increase of injection current. 47
- Figure 3.5** Radiation loss of the four lowest loss leaky modes plotted against the first cladding layer width s with $d_1 = 12 \mu\text{m}$ and $d_2 = 3.9 \mu\text{m}$. The four leaky modes LM_{01} , LM_{11} , LM_{02} , LM_{12} are identified by solid, dashed-dotted, dotted, and dashed lines, respectively 48
- Figure 3.6** Field-intensity profile of leaky modes (a) LM_{01} (solid line) and LM_{02} (dotted line) and (b) LM_{11} (dashed-dotted line) and LM_{12} (dashed line), with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, and $d_2 = 3.9 \mu\text{m}$ 49
- Figure 3.7** Field-intensity profile of LM_{11} in (a) a conventional ARROW VCSEL and (b) an ARROW VCSEL designed based on the new approach.....50
- Figure 3.8** (a) L-I curve and (b) side-mode suppression ratio for ARROW VCSEL designed using conventional approach (dash-dotted line) and new approach (solid line).....51
- Figure 3.9** Radiation loss of the four lowest loss leaky modes plotted against s , with (a) $d_1 = 12 \mu\text{m}$ and $d_2 = 6 \mu\text{m}$ and (b) $d_1 = 8 \mu\text{m}$ and $d_2 = 4 \mu\text{m}$ 53

Figure 3.10 Turn-on transient response of (a) output power, (b) net modal gain, (c) radiation loss, (d) N_{c0} and (e) N_{c2} . The solid and dash-dotted lines represent LM_{01} and LM_{11} , respectively.....	55
Figure 4.1 Schematic of an ARROW VCSEL under the influence of external optical feedback.....	62
Figure 4.2 Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, and $d_2 = 6 \mu\text{m}$ when injection current density is (a) 6.5 kA/cm^2 , (b) 7 kA/cm^2 , and (c) 8.5 kA/cm^2 . ■ - LM_{01} and • - LM_{11} . The inserts give the transient response of LM_{01} (solid line) and LM_{11} (dashed line) over a time period of 2 ns.	65
Figure 4.3 Radiation loss of the four lowest loss leaky modes plotted versus s with $d_2 = 3.9 \mu\text{m}$. Solid line – LM_{01} , dashed-dot line – LM_{11} , dashed line – LM_{02} , and dotted line – LM_{12}	67
Figure 4.4 Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, and $d_2 = 3.9 \mu\text{m}$ when injection current density is (a) 5.82 kA/cm^2 , (b) 6.42 kA/cm^2 , and (c) 7.22 kA/cm^2 . ■ - LM_{01} and • - LM_{11}	68
Figure 4.5 Plot of maximum k_{ext} versus total output power for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, $d_2 = 6 \mu\text{m}$ (‘■’-minimum threshold current) and that with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, $d_2 = 3.9 \mu\text{m}$ (‘•’- maximum radiation loss margin).....	69
Figure 5.1 Schematic of the birefringent ARROW VCSEL used in the analysis	75

- Figure 5.2** (a) Light-current curves and (b) net gain versus normalized injection current for the birefringent ARROW VCSELs with $s = 1.3 \mu\text{m}$, $d_2 = 6 \mu\text{m}$, $\Delta n_c = 2 \times 10^{-4}$, and $\Delta n_s = 0$ (reference point) for the four transverse leaky modes..... 79
- Figure 5.3** (a) Plots of radiation loss of LM_{01} versus s and d_2 . The inserted diagram is the enlargement of radiation loss of LM_{01} in range of $1 \mu\text{m} < s < 1.5 \mu\text{m}$ and $2 \mu\text{m} < d_2 < 6 \mu\text{m}$. (b) Radiation loss difference between LM_{01}^v and LM_{01}^h for Δn_v varies between 2×10^{-4} and 1×10^{-3} 82
- Figure 5.4** (a) Light-current curves and (b) net gain versus normalized injection current for the new designed birefringent ARROW VCSELs with $s = 1.68 \mu\text{m}$, $d_2 = 3.93 \mu\text{m}$, $\Delta n_v = 2 \times 10^{-4}$, and $\Delta n_h = 0$ for the four polarized transverse leaky modes..... 83
- Figure 6.1** Schematic of an ARROW VCSEA operating in reflection mode. 89
- Figure 6.2** Amplifier gain versus (a) input signal wavelength and, (b) pump current of an ARROW VCSEA with $d_1 = 12 \mu\text{m}$, $s = 2.89 \mu\text{m}$, $d_2 = 6 \mu\text{m}$. The arrows indicate the increase of pump current (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$). λ_{p01} and λ_{p11} are the resonant wavelength of LM_{01} and LM_{11} , respectively..... 97
- Figure 6.3** Amplifier gain versus (a) input signal wavelength and, (b) pump current of a conventional index-guided VCSEA with $d_1 = 12 \mu\text{m}$, $n_1 = 3.3$ and $n_2 = n_3 = n_4 = 3.25$. The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$)..... 98

- Figure 6.4** Transverse distributions of (a) carrier concentration, (b) carrier-induced index change, (c) temperature and heat-induced index change, (d) total index change and (e) field intensity of LM₀₁ and LM₁₁ versus pump current. The arrows indicate the increase of J (from 0.6, 0.8 to $0.98 \times J_{th}$). (f) Amplifier gain versus signal wavelength for $J = 0.6$ and $0.98 \times J_{th}$. The dashed lines indicate the calculation without the consideration of SHB and thermal lensing. 100
- Figure 6.5** Amplifier gain versus signal wavelength for $J = 0.6$ and $0.98 \times J_{th}$ of index-guided VCSOAs with $d_1 = 12 \mu\text{m}$. The dashed lines indicate the calculation without the consideration of SHB and thermal lensing..... 102
- Figure 6.6** Transverse distribution of (a) carrier concentration, (b) carrier-induced and heat-induced index changes, (c) total index change versus input signal power. (d) Amplifier gain of LM₀₁ and LM₁₁ versus input signal power. The arrows indicate the increase in $P_{I,01}$ (from -50 dBm to -10 dBm with 10 dBm interval)..... 103
- Figure 6.7** Amplifier gain of LM₀₁ and LM₁₁ versus input signal power of index-guided VCSOAs with $d_1 = 12 \mu\text{m}$. The arrows indicate the increase in $P_{I,01}$ (from -50 dBm to -10 dBm with 10 dBm interval)..... 105
- Figure 6.8** Radiation loss margin between LM₀₁ and the next lowest-loss transverse mode versus s and d_2 for ARROW VCSOA with (a) $d_1 = 12 \mu\text{m}$, (b) $d_1 = 20 \mu\text{m}$, (c) $d_1 = 30 \mu\text{m}$, (d) $d_1 = 50 \mu\text{m}$ 109

- Figure 6.9** Amplifier gain versus (a) signal wavelength and, (b) pump current for an ARROW VCSOA with $d_1 = 12 \text{ } \mu\text{m}$, $s = 2.12 \text{ } \mu\text{m}$, $d_2 = 3.96 \text{ } \mu\text{m}$. The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$). 110
- Figure 6.10** Transverse distributions of (a) carrier concentration, (b) carrier-induced index change, (c) temperature and heat-induced index change, (d) total index change and (e) field intensity of LM_{01} and LM_{11} . The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$). The ARROW VCSOA has dimensions of $d_1 = 12 \text{ } \mu\text{m}$, $s = 2.12 \text{ } \mu\text{m}$ and, $d_2 = 3.96 \text{ } \mu\text{m}$ 112
- Figure 6.11** Transverse distribution of (a) carrier concentration, (b) carrier-induced and heat-induced index changes, (c) total index change and, (d) field intensity versus input signal power. (e) Amplifier gain of LM_{01} and LM_{11} versus input signal power. The arrows indicate the increase of $P_{\text{I},01}$ (from -50 dBm to -10 dBm with 10 dBm interval). The ARROW VCSOA has dimensions of $d_1 = 12 \text{ } \mu\text{m}$, $s = 2.12 \text{ } \mu\text{m}$ and, $d_2 = 3.96 \text{ } \mu\text{m}$ 113
- Figure 6.12** Variation of (a) amplifier gain and bandwidth and, (b) saturation power versus d_1 . The methods to measure bandwidth and saturation power are shown in (c) and (d), respectively. 115

List of Tables

Table 3.1 Device and Material Parameters (used in the analysis of transverse leaky modes of ARROW VCSELs)	43

Table 5.1 Device and Material Parameters (used in the analysis of polarization switching characteristics of ARROW VCSELs).....	78

CHAPTER 1

Introduction

1.1 Motivation

During the past two decades, optoelectronic semiconductor devices such as lasers and optical amplifiers have found enormous applications in telecommunication systems. The further development of semiconductor lasers and amplifiers was driven by the rapidly expanding telecommunication market and the emerging next-generation high-speed telecommunication networks [1]. Vertical cavity surface emitting lasers (VCSELs) and vertical cavity semiconductor optical amplifiers (VCSOAs) are two of the latest achievements in semiconductor optoelectronic devices.

VCSELs are semiconductor lasers with an ultra small vertical cavity. For VCSELs, light is emitted from the surface of the lasers. However, light is emitted from the edge of the conventional edge-emitting lasers. VCSEL was first proposed and fabricated in the year 1979 [2]. It had received almost no attentions at that time due to the difficulty to obtain high optical gain in bulk materials and highly reflective mirrors. The situation was changed in the late 1990s by the research achievements in the fabrication of quantum-well materials and distributed Bragg reflectors (DBRs) using molecular beam

epitaxy (MBE) technique. Meanwhile, the tremendous demand in Internet communications has brought the urgent needs for the rapid interchange and sharing of huge-volume information. The conventional LED transmitter became the bottle-neck of the network bandwidth due to its low modulation speed. VCSELs were found to be a good replacement of LEDs due to the low-cost, high-speed and high reliability. Hence, VCSELs are believed to be the key component to enable the next-generation high-speed networks. Since then, VCSEL has become a hotspot in the research of optoelectronic devices. Presently, VCSEL market has become a billion dollar industry which is still expanding. Figure 1.1 shows the information from a recent market report by Communications Industry Researchers (CIR). It says that more than 100,000 units of VCSELs were shipped in year 2006 and even more shipments are predicted in 2007 and 2008. [3]

Figure 1.1 VCSEL shipments statistics and prediction for 2005-2008
(courtesy of CIR)

VCSELs have shown advantages over conventional edge emitting lasers in many applications, such as displays, sensors, printing and lighting products. The most important advantage of VCSELs over edge emitting lasers is the simplicity of wafer testing procedures. VCSEL's vertical structure allows on-wafer testing before dicing and packaging, which significantly reduces the production cost. In addition, the capability of surface emission and extremely compact size facilitate the realization of laser arrays on wafer. [4] Furthermore, there are other advantages of VCSELs including (1) low beam divergence; (2) low power consumption; (3) high modulation bandwidth; and (4) easy polarization control. [5, 6].

VCISOAs are the design of semiconductor optical amplifiers using VCSEL technology. The special structure gives VCISOAs a number of advantages over the conventional in-plane semiconductor optical amplifiers (SOAs). Some of these advantages are inherited from VCSELs, including the possibility for on-wafer testing, high coupling efficiency to optical fiber, small form factor, low power consumption, easy polarization control and the possibility to form 2-D arrays. Other advantages of VCISOAs are some unique optical characteristics of the amplifiers. For example, VCISOAs have very narrow gain bandwidth due to the high reflectivity of the DBR mirrors. The narrow bandwidth can filter out noise from undesired wavelengths, which makes VCISOAs ideal as optical filters. The high coupling efficiency also benefits it for achieving a low noise figure. It is believed VCISOAs is a cost-effective alternative to erbium-doped fiber amplifiers (EDFAs) used in telecommunication networks [7].

Short-wavelength (i.e., $\lambda \leq 980\text{nm}$) VCSELs have been successfully commercialized and widely used in short-distance optical communication networks as the light emitting sources. Long-wavelength (i.e., $\lambda \sim 1300/1500\text{ nm}$) VCSELs are of particular interests to replace distributed feedback (DFB) lasers in long-distance high-speed optical fiber communication systems due to VCSELs' high modulation speed, low power consumption and low production cost. However, the maximum output power of VCSELs is limited due to its small cavity size. The modal and polarization stabilities of VCSELs are also affected by the symmetric orientation of the laser cavities. Therefore, one big challenge for VCSEL designers is to develop novel design of VCSELs which can operate at high output power ($>10\text{ mW}$) and single transverse mode (side mode suppression ratio $>40\text{ dB}$). [1] The VCSEL should also maintain the polarization stability and be robust against the disturbance from external optical feedback during the operation.

The maximum output power of VCSELs can be scaled up with the aperture area of the active layer. Current technology of semiconductor lasers can fabricate VCSELs with aperture area $\geq 16\text{ }\mu\text{m}$ and the maximum output power can be larger than 40mW [8]. However, the problems of such a large aperture may lead to multiple transverse modes operation and instability of polarization switching in VCSELs. High order transverse-modes emission and the polarization instability significantly decrease the overall performance of telecommunication systems. In addition, it is expected that VCSELs with large aperture will be more sensitive to external optical feedback than that of small aperture devices. Therefore, high-power (i.e. large aperture area) VCSELs are more inclined to emit an unstable output than low-power devices. This problem

has significantly limited the use of VCSELs in applications that demand high output power and output stability simultaneously.

It is believed that VCISOAs will face challenges similar to that of VCSELs in order to maintain single-mode operation at high emission intensity. The difficulty to achieve stable output power from large-area VCSELs and VCISOAs is mainly due to insufficient transverse optical confinement of the devices' cavities. Different methods have been proposed to improve the control of transverse optical confinement of the transverse optical field inside the laser cavities. They included the design of gain-guided, index-guided, anti-guided structures. All of them have certain advantages but each of them is either limiting the output power or with great fabrication complexity.

1.2 Objective

The overall objective of this thesis is to optimize the design of large-area VCSELs and VCISOAs so that they can generate single-mode high-power output laser beam with maximum stability.

In order to achieve this objective, it is most essential to find an appropriate design of transverse optical confinement for VCSELs and VCISOAs. In this thesis, we proposed to use a new design of transverse optical confinement, anti-resonant reflecting optical waveguide (ARROW), to achieve stability and high output power emission simultaneously. ARROW makes use of selective radiation losses to suppress the higher order transverse modes so that only fundamental transverse mode will be supported. There has been experiment report showing ARROW's promising single-mode performance. [9] We have

applied ARROW in large-area VCSELs and VCISOAs to achieve stable single-mode high-power emission.

1.3 Major Contributions of the Thesis

The major contributions of this work are summarized as follows:

- The theoretical models that are capable for the comprehensive study of multi-transverse-mode, polarization, feedback characteristics of large-area ARROW VCSELs have been established. The complex transverse optical field profiles of the multiple transverse modes, as well as the spatial-hole burning and thermal effects existing in large-area devices, are well described in this model with a good balance between simulation accuracy and runtime.
- Optical characteristics of large-area ARROW VCSELs have been intensively studied. These included the multi-transverse modes competition, polarization switching, and emission characteristics under external optical feedback. The analysis of these characteristics provides a good overall understanding to the stability of ARROW VCSEL devices.
- Based on the analysis of the optical characteristics of ARROW VCSELs, structure optimization methods have been proposed to enhance ARROW VCSELs' output stability. Comparisons have also been made between optimized ARROW VCSELs, non-optimized

ARROW VCSELs and VCSELs with conventional confinement in order to evaluate the new design methods.

- The idea of using ARROW to confine VCISOAs is also proposed. A detailed theoretical model for the comprehensive analysis of ARROW VCISOAs is established. The model is capable of analyzing several most important amplifier characteristics of ARROW VCISOAs, as well as the influence of aperture area change on these characteristics.
- The most important optical characteristics of large-area ARROW VCISOAs, including the amplifier gain, bandwidth and saturation power, have been intensively investigated. The study also illustrates how the device area and confinement structure influence the stability of the output amplified signal, as well as the other optical characteristics.
- Optimized design methods are proposed for large-area ARROW VCISOAs to maximize the stability of the amplified output signal, based on the analysis of their optical characteristics.

To summarize, this thesis presents a detailed analysis of the optical characteristics of large-area ARROW VCSELs and VCISOAs. It also provides structure design optimization methods for large-area VCSELs and VCISOAs that are suitable for the use in high-power single-mode applications.

1.4 Organization of the Thesis

These contents of this thesis are organized as follows:

Chapter 2: Background and Literature Review. In this chapter, the operation principles of VCSELs, VCISOAs and ARROW, as well as their recent developments are briefly reviewed. The limitations of the conventional VCSELs and VCISOAs as well as the corresponding transverse confinement methods are discussed.

Chapter 3: Analysis of the Transverse Leaky Modes of Large-area Antiresonant Reflecting Optical Waveguide Vertical Cavity Surface Emitting Lasers. In this chapter, a fast and accurate model to simulate the transverse optical field profile in the cylindrical ARROW structure is introduced, which is incorporated into the rate equation model for large-area VCSELs and form a self-consistent model system. With this model system, the transverse leaky cavity modes in ARROW VCSELs are investigated carefully. The mechanism of higher order transverse modes excitation and its prevention are the focus of the study. Based on the analysis, a new design method is proposed to optimize the ARROW structure for more robust single-mode output lasing. The stability of the ARROW VCSELs designed by the new method is compared with that of index-guided VCSELs, as well as ARROW VCSELs with the initial design, to demonstrate the effectiveness of the new design method.

Chapter 4: Study of ARROW VCSELs under External Optical Feedback. The single-mode stability of high-power ARROW VCSELs can be disturbed by the external optical feedback. Therefore investigation to

ARROW VCSELs' response to external optical feedback makes significant sense. ARROW VCSELs' transient response to the external optical feedback is the study focus in this chapter. Optimization design method is also proposed based on the study to enhance the output stability robustness against the external optical feedback.

Chapter 5: Suppression of Polarization Switching in Birefringent ARROW VCSELs. Polarization switching is another effect that is frequently observed in the high power operations of VCSELs. Single polarization operation is essential in many VCSEL applications. Therefore it is of great importance to suppress the switching from happening. It is believed the polarization switching is a result of the inevitable material birefringence of the active layer. In this chapter, the competition between the two orthogonal polarizations of birefringent ARROW VCSELs is investigated. The root causes of the polarization switching are analyzed. Based on the understanding to the polarization switching root cause, a new method to control the polarization switching by carefully tuning the structure of ARROW is proposed and has demonstrated significant effectiveness for the suppression of polarization switching.

Chapter 6: Analysis and Design of Large Area Antiresonant Reflecting Optical Waveguide Vertical Cavity Semiconductor Optical Amplifiers.

In this chapter, the theoretical model of large area VCSEA has been developed. Similarly to the building of VCSEL model, the amplifier equations initially for small-area VCSEAs are enriched by the integration of transverse optical field model. Using this model, the amplifier gain difference

between the fundamental and side transverse cavity modes are calculated. This difference is believed to be directly related to the output signal stability of ARROW VCISOAs. By monitoring the variation of this difference with the change of pump and input signal power, the main contributor to the instability is identified. An optimized design solution is proposed to minimize the factors that contribute to the instability and therefore maximize the output signal stability of ARROW VCISOAs.

Chapter 7: Conclusions. This chapter concludes all the work demonstrated in this thesis.

REFERENCES

- [1] S. F. Yu, "*Analysis and design of vertical cavity surface emitting lasers*". 1st edition, New York: John Wiley & Son, 2003.
- [2] H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, "GaInAsP/InP surface emitting injection lasers," *Jpn. J. Appl. Phys*, vol. 18, p. 2329-2330, 1979.
- [3] M. Hatcher, "Ethernet evolution to drive VCSEL ramp," in *Compound Semiconductor*, January 2006.
- [4] K. D. Choquette and H. Q. Hou, "Vertical-cavity surface emitting lasers: moving from research to manufacturing," *Proceedings of the IEEE*, vol. 85, pp. 1730-1739, 1997.
- [5] W. W. Chow, K. D. Choquette, M. H. Crawford, K. L. Lear, and G. R. Hadley, "Design, Fabrication, and Performance of Infrared and Visible Vertical-Cavity Surface-Emitting Lasers," *IEEE Journal of Quantum Electronics*, vol. 33, 1997.
- [6] D. Tauber, G. Wang, R. S. Geels, J. E. Bowers, and L. A. Coldren, "Large and small signal dynamics of vertical cavity surface emitting lasers," *Applied Physics Letters*, vol. 62, pp. 325-327, 2006.
- [7] E. S. Bjorlin, T. Kimura, and J. E. Bowers, "Carrier-confined vertical-cavity semiconductor optical amplifiers for higher gain and efficiency," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 9, pp. 1374-1385, Sep-Oct, 2003.
- [8] W. Schmid, D. Wiedenmann, M. Grabherr, R. Jager, R. Michalzik, and K. J. Ebeling, "CW operation of a diode cascade InGaAs quantum well VCSEL," *Electronics Letters*, vol. 34, pp. 553-555, Mar 1998.
- [9] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.

CHAPTER 2

Background and Literature Review

This chapter reviews the operation principles and recent developments of ARROW VCSELs and VCISOAs. The limitations of current VCSELs and VCISOAs and their existing confinement methods are also discussed.

2.1 Vertical Cavity Surface Emitting Lasers

The basic structure of a VCSEL is shown in Figure 2.1. An active layer containing gain material is sandwiched by two highly refractive mirrors. The laser can be optically or electrically pumped. Photons inside the cavity are amplified each time passing through the active layer when they travel along the

Figure 2.1 Basic structure of an electric-pumped VCSEL

vertical direction. When the lasing threshold is reached, light beam will emit normally from the top or bottom surface. In order to achieve a low lasing threshold, the cavity length of VCSELs is designed to be extremely short (1~2 μm) and the active layer is made of high optical gain materials to provide strong single-pass amplification of the optical field. Furthermore, the reflectivity of the cavity mirrors is selected to be of high magnitude to obtain sufficient feedback.

The first VCSEL was fabricated by K. Iga in the late 1970s [1]. It was an electrically pumped VCSEL under pulse operation at 77K. The same group also reported the first room-temperature pulse VCSEL and the first continuous-wave (CW) VCSEL several years later [2]. A milestone for VCSEL development is their achievement of the first room-temperature CW VCSEL in 1989 [3]. Since then, the realization of low-threshold, high-power VCSELs has become an important target of VCSEL research.

In order to decrease the lasing threshold and increase the output power, researchers have been making great efforts to improve the medium gain of the active layer, as well as the reflectivity of the cavity mirrors. In the early developments of short-wavelength VCSELs, bulk gain materials and metal-based dielectric mirrors were used. They were replaced by quantum-well (QW) materials and distributed Bragg reflectors (DBR) in the later developments of VCSELs, especially long-wavelength VCSELs. QW materials and DBRs provide much higher optical gain and reflectivity, so they can significantly decrease the lasing threshold of VCSELs. A sub-milliampere threshold current under CW operation at room temperature is achievable currently.

The rapid development of GaAs-based VCSELs has led to the successful commercialization of short wavelength VCSELs. Now short-wavelength (i.e. 850-980-nm) VCSELs have been widely adopted in various areas, especially in short-distance multi-mode optical fiber communications due to the higher modulation speed and lower production cost. Long wavelength VCSELs are also believed to be valuable in communication systems. They are a good replacement of short-wavelength VCSELs in LANs for higher transmission speed. High-power single-mode long-wavelength VCSELs are also an ideal replacement of the DFB lasers in metropolitan area networks (MAN) and long-haul high-speed optical fiber communication systems.

However, the development of long-wavelength (i.e. 1300–1550-nm) VCSELs suffers from several difficulties, including the difficulty to find lattice-match highly reflective DBR materials, high internal absorption loss, low thermal conductivity, small conduction band offset, and so on. Despite these drawbacks, 1300-nm and 1550-nm VCSELs under pulse operation at room temperature have both been achieved [4, 5]. However, these VCSELs still suffer high threshold current and low output power problems. Lower threshold current and higher output power can be achieved by using fusion bonding method, but this method requires complicated fabrication procedures and will yield a very high production cost.

2.2 Confinement configurations of VCSELs

Low threshold current and high output power are desirable in the realization of long-wavelength VCSELs. In addition, as has been mentioned in the preceding chapter, there is another upcoming challenge is to achieve the stable single transverse mode, single polarization lasing emission and sufficient robustness against external feedback. These characteristics are all in relation with the transverse optical confinement of VCSELs.

The cavity orientation difference between VCSELs and edge emitting lasers makes their optical confinement design strategies differ. Edge emitting lasers' long cavity length allows the residence of several longitudinal cavity modes, so the longitudinal optical confinement dominates the multiple cavity mode characteristics. However longitudinal confinement is less important in VCSEL due to its ultra-short cavity length so that only one longitudinal mode can be accommodated. Therefore the transverse optical confinement of VCSELs determines the modal and polarization characteristics.

Gain-guided, index-guided and anti-guided structures are the conventional methods to confine transverse modes in VCSELs. Gain-guided structure was commonly used in the early-stage in developing VCSELs. A circular metal contact is applied close to active layer, so that the injection carriers can be launched into the area defined by the contact. The majority of the optical gain is preserved inside the core region. As a result, the transverse optical modes are confined by the transverse gain profile. Gain-guided confinement can be enhanced by ion implantation to the p-DBR [6].

Figure 2.2 Schematic of a typical gain-guided VCSEL with ion-implantation.

Figure 2.2 shows the schematic of a typical gain-guided VCSEL with ion-implantation. The implanted region has larger electrical resistivity so that the injected current is better confined. The major advantage of this structure is its simplicity for fabrication. However, it is not effective to control the carrier concentration along the transverse direction of active layer, which is an important contribution to higher order transverse modes excitation via carrier induced refractive index change, by the metal contact.

Index-guided structure is a much better confinement method for transverse optical field. Index-guided VCSELs have the following types: air-posted, etched mesa, regrowth buried heterostructure and oxide aperture. Among these types, oxide aperture VCSEL is now the most promising devices for replacing LEDs in LAN and MAN networks.

Figure 2.3 shows a typical double oxide aperture index-guided VCSEL [7]. The refractive index of the oxide aperture is lower than that of the core region material. Hence, the resulted effective index difference between the cavity and the surrounding oxide aperture region can confine the transverse optical field. The index difference can be tuned by changing the oxide thickness. Furthermore, the oxide aperture is good insulator that can also confine the injection current into the core region, which will enhance the wall-plug efficiency. Therefore, oxide aperture VCSELs may exhibit ultra low threshold current [8] and high wall-plug efficiency [9]. The oxidation process will also not significantly increase the production cost as it is compatible with the monolithic growth of GaAs-based material systems.

However, there are two problems that limit the performance of oxide aperture

Figure 2.3 Schematic of an index-guided VCSEL with double oxide aperture.

VCSELs: One is the high refractive index contrast between the oxide and the core region, which facilitates the excitation of higher-order transverse modes. The other problem is the confinement will fail with a very large aperture size. This limited aperture size also limits the maximum output power. Although the problems can be avoided by using some special waveguide structures, like tapered waveguide, it is not preferred due to its fabrication complexity.

Anti-guided structure is a possible design to realize high-power single-mode operation of VCSELs and VCISOAs. Figure 2.4 shows a possible design of anti-guided VCSEL [10]. The transverse effective refractive index profile is also given. A thick low-temperature (LT) layer with enhanced resistivity and an undoped cap layer are grown on top of the p layer. These two additional layers can confine the injected carrier concentration, as well as change the transverse refractive index profile. It is noted the core region of the cavity has a lower effective refractive index and thus form a leaky waveguide. Higher-order transverse modes will suffer larger radiation loss than that of the fundamental transverse mode in this leaky waveguide.

Figure 2.4 Schematic of an antiguided VCSEL and the corresponding profile of transverse effective refractive index.

It is reported that high-order transverse modes was significantly suppressed at high injection level on an anti-guided VCSEL with a core diameter as large as $6\ \mu\text{m}$ [10]. The drawback of this structure is the fundamental transverse mode will also suffer from large radiation loss, which results in a high threshold injection current and a low wall-plug efficiency.

The anti-guided structure is not preferable because it will increase the threshold current of the VCSELs, but the idea of using high radiation loss to suppress the higher-order transverse modes is applicable. The challenge is to find a way to minimize the radiation loss of the fundamental transverse mode. This can be achieved by adding two more rings of cladding layers at the transverse direction of the antiguided structure. This modified structure was named antiresonant reflecting optical waveguide (ARROW) [11]. Figure 2.5

shows the transverse effective index profile inside an ARROW structure. A low-index core region is surrounded by two cladding layers of thicknesses s and d_2 , respectively. s and d_2 are carefully selected according to the effective transverse wavelength of the fundamental transverse mode, so that the optical field of this desired mode fulfills the antiresonant condition. As a result, the radiation loss of this transverse mode is minimized.

To better illustrate this, the transverse optical field of the fundamental mode in a typical ARROW waveguide is also given in Figure 2.5. It is shown that the waveguide supports fundamental transverse mode in the condition of antiresonance. There is a node (anti-node), where the transverse optical field has absolute minimum (maximum) amplitude, at the interface between core and first cladding layer (first and second cladding layer). The optical field inside two cladding layers thus can be destructively interfered and the radiation loss is

Figure 2.5 Transverse effective refractive index profile of a typical cylindrical ARROW structure and the transverse optical field of the fundamental mode inside it.

minimized. The other high-order transverse modes have different effective transverse wavelength so do not meet the antiresonant condition, and therefore will experience high radiation losses. Therefore, high order transverse modes are suppressed and only the fundamental transverse mode is preserved. Comparing ARROW with other waveguide structures, we can find ARROW structure has the following advantages:

- Higher order transverse modes can be effectively suppressed and the fundamental transverse mode only experienced a minor radiation loss. Hence, single transverse mode output and high wall-plug efficiency can be achieved simultaneously.
- The aperture (core) diameter can increase to a much larger value than that of the gain-guided and index-guided structures without producing any unstable multi-mode output. Higher power output is therefore achievable.

2.3 ARROW VCSELS

It was reported that a cylindrical ARROW VCSEL has been fabricated with significant reduction of radiation loss of the fundamental transverse mode [12]. It has a diameter of 8 μm and a maximum single-mode CW power of 7.1 mW. The maximum single-mode power is higher than that of a conventionally confined VCSEL. However, it was also reported with a larger aperture diameter, multi-transverse-mode emission was observed. This is because their design of the ARROW structure (e.g. the selection of s and d_2) was based on a cold-cavity simulation with a planar approximation when calculating the

effective transverse wavelength. We believed that by using a more accurate simulation model, the ARROW structure can be optimized to achieve a higher single-mode output emission.

It is therefore believed that ARROW is a suitable confinement structure in the realization of high-power single-mode VCSELs. However, the non-optimized ARROW design from an over-approximated simulation has limited capability to increase the maximum single-mode output power. A higher maximum single-mode output power can be achieved, which will be illustrated in details in the following chapters.

ARROW VCSELs also demonstrated other advantages such as higher controllability to polarization switching and enhanced single mode robustness against external feedback. These contributions to the overall stability of the VCSEL output will be discussed in details in the following chapters as well.

2.4 ARROW VCSOAs

The operation principle of vertical-cavity semiconductor-optical-amplifiers (VCSOAs) can be understood as VCSELs under below threshold biasing to function as optical amplifiers. Their only structure difference is that the structure of VCSOA is optimized as an amplifier as opposed to an oscillator. For example, the reflectivity of the DBRs of VCSOAs is often made lower than that of VCSELs to avoid lasing. VCSOAs can also be pumped optically or electrically. If the signal is introduced in and emitted out through the same mirror, then this VCSOA is operated in reflection mode. Otherwise, it is operated in transmission mode. The two operation modes are illustrated in

Figure 2.6. The design criteria of VCSEA normally focus on the optimization of its amplifier gain, gain bandwidth, saturation power and noise figure.

VCSEA was first presented by the same group who invented VCSEL at Tokyo Institute of Technology in 1991 [13]. They used an electrically pumped GaAs/AlGaAs VCSEL to amplify and filter an injected 885-nm signal. In fact, this first VCSEA was not presented as an amplifier but an active filter. The VCSEA showed about 4 dB internal gain but no fiber-to-fiber gain was recorded. In 1993, the first optically pumped reflection mode VCSEA was presented by researchers in France Telecom [14]. It was a short wavelength (850-nm) VCSEA and only pulse operation was reported. In 1996, they reported the first long-wavelength (1.55- μ m) VCSEA with 14-dB gain in pulse operation [15]. Another 980-nm electrically pumped VCSEA was report in this year by researchers in University of Ulm [16]. In 1998, the same group presented an electrically pumped, transmission-mode 980-nm VCSEA with an

Figure 2.6 Two operation modes of VCSEA: transmission mode (left) and reflection mode (right).

oxide aperture to confine the current and optical mode, with a 16-dB gain [17]. The first electrically pumped long-wavelength (1.55 μm) VCSEA was fabricated by a research group in Royal Institute of Technology (KTH) in Sweden, also in 1998 [18]. The device was with 18-dB gain at 218 K not including coupling losses. In 2000 and 2002, researchers in University of California, Santa Barbara (UCSB) presented two generations of 1.3 μm VCSEAs [19, 20]. Both generations are optically pumped by a 980-nm laser and both of them are designed for reflection-mode operation. The successful fabrication of long-wavelength VCSEAs provide great possibility to replace the conventional in-plane SOAs in numerous applications. The largest potential market is the optical fiber communication market as the existing erbium-doped fiber amplifiers (EDFAs) widely used in long-haul optical fiber communications can be replaced by the high-speed, high-reliable and low-cost long-wavelength VCSEAs.

The optical confinement of VCSEAs mainly uses gain-guided and carrier-confined (index-guided) structures, which is similar to VCSELs. Normally the optical transverse confinement of VCSEA was not emphasized in the device design as it is not as critical as that of VCSEL's. However, in VCSEAs' high-power applications, higher output saturation power is usually achieved by increasing the device's core diameter. When the output saturation power (i.e. the core diameter) increases to a certain level, multi-transverse-mode emission (i.e., unstable single-mode output) can be observed. There is report that unstable output signal is displayed in a VCSEA with core diameter of 50 μm [21]. The confinement design will therefore become a significant challenge, just like what happened in the design of VCSELs. Due to the structure similarity between

VCISOAs and VCSELs, we believe the instability can be minimized through similar confinement method as used in VCSELs. Hence, ARROW VCISOA is proposed to realize the high power operation of VCISOAs with great stability. The theoretical exploration of ARROW VCISOAs will be presented in the following chapters.

2.5 Conclusion

To conclude, the basic operation principles and recent developments of VCSELs and VCISOAs have been reviewed in this chapter. The transverse optical confinement is a critical challenge in the design and fabrication of VCSELs and VCISOAs. The conventional transverse confinement methods are either not able to suppress the higher-order transverse modes effectively or will limit the maximum output power of VCSELs and VCISOAs. The application of ARROW to VCSELs and VCISOAs is believed to be a promising approach to realize stable single-mode operation and high power output simultaneously. However, it is necessary to improve the existence ARROW design method to obtain the required performance.

REFERENCES

- [1] H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, "GaInAsP/InP surface emitting injection lasers," *Jpn. J. Appl. Phys.*, vol. 18, pp. 2329-2330, 1979.
- [2] K. Iga, S. Ishikawa, S. Ohkouchi, and T. Nishimura, "Room-Temperature Pulsed Oscillation of GaAlAs/GaAs Surface Emitting Injection-Laser," *Applied Physics Letters*, vol. 45, pp. 348-350, 1984.
- [3] F. Koyama, S. Kinoshita, and K. Iga, "Room-Temperature Continuous Wave Lasing Characteristics of a GaAs Vertical Cavity Surface-Emitting Laser," *Applied Physics Letters*, vol. 55, pp. 221-222, Jul 1989.
- [4] P. Salet, F. Gaborit, P. Pagnod-Rossiaux, A. Plais, E. Derouin, J. Pasquier, and J. Jacquet, "Room-temperature pulsed operation of 1.3 μm vertical-cavity lasers including bottom InGaAsP/InP multilayer Bragg mirrors," *Electronics Letters*, vol. 33, pp. 2048-2049, Nov 1997.
- [5] J. Boucart, C. Starck, F. Gaborit, A. Plais, N. Bouche, E. Derouin, L. Goldstein, C. Fortin, D. Carpentier, P. Salet, F. Brillouet, and J. Jacquet, "1-mW CW-RT monolithic VCSEL at 1.55 μm ," *IEEE Photonics Technology Letters*, vol. 11, pp. 629-631, Jun 1999.
- [6] Y. J. Yang, T. G. Dziura, T. Bardin, S. C. Wang, and R. Fernandez, "Continuous Wave Single Transverse-Mode Vertical-Cavity Surface-Emitting Lasers Fabricated by Helium Implantation and Zinc Diffusion," *Electronics Letters*, vol. 28, pp. 274-276, Jan 1992.
- [7] T. H. Oh, D. L. Huffaker, and D. G. Deppe, "Comparison of vertical-cavity surface-emitting lasers with half-wave cavity spacers confined by single- or double-oxide apertures," *IEEE Photonics Technology Letters*, vol. 9, pp. 875-877, Jul 1997.
- [8] G. M. Yang, M. H. Macdougall, and P. D. Dapkus, "Ultralow Threshold Current Vertical-Cavity Surface-Emitting Lasers Obtained with Selective Oxidation," *Electronics Letters*, vol. 31, pp. 886-888, May 1995.
- [9] P. W. Evans, J. J. Wierer, and N. Holonyak, " $\text{Al}_x\text{Ga}_{1-x}\text{As}$ native-oxide-based distributed Bragg reflectors for vertical cavity surface emitting lasers," *Journal of Applied Physics*, vol. 84, pp. 5436-5440, Nov 1998.
- [10] T. H. Oh, O. B. Shchekin, and D. G. Deppe, "Single-mode operation in an antiguided vertical-cavity surface-emitting laser using a low-temperature grown AlGaAs dielectric aperture," *IEEE Photonics Technology Letters*, vol. 10, pp. 1064-1066, Aug 1998.

- [11] D. Zhou and L. J. Mawst, "Simplified-antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *Applied Physics Letters*, vol. 76, pp. 1659-1661, Mar 27 2000.
- [12] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.
- [13] F. Koyama, S. Kubota, and K. Iga, "GaAlAs/GaAs Active-Filter Based on Vertical Cavity Surface Emitting Laser," *Electronics Letters*, vol. 27, pp. 1093-1095, Jun 1991.
- [14] R. Raj, J. A. Levenson, J. L. Oudar, and M. Bensoussan, "Vertical Microcavity Optical Amplifying Switch," *Electronics Letters*, vol. 29, pp. 167-169, Jan 1993.
- [15] N. Bouche, B. Corbett, R. Kuszelewicz, and R. Raj, "Vertical-cavity amplifying photonic switch at 1.5 μm ," *IEEE Photonics Technology Letters*, vol. 8, pp. 1035-1037, Aug 1996.
- [16] D. Wiedenmann, B. Moeller, R. Michalzik, and K. J. Ebeling, "Performance characteristics of vertical-cavity semiconductor laser amplifiers," *Electronics Letters*, vol. 32, pp. 342-343, Feb 1996.
- [17] D. Wiedenmann, R. King, C. Jung, R. Jager, R. Michalzik, P. Schnitzer, M. Kicherer, and K. J. Ebeling, "Design and analysis of single-mode oxidized VCSEL's for high-speed optical interconnects," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 5, pp. 503-511, May-Jun 1999.
- [18] R. Lewen, K. Streubel, A. Karlsson, and S. Rapp, "Experimental demonstration of a multifunctional long-wavelength vertical-cavity laser amplifier-detector," *IEEE Photonics Technology Letters*, vol. 10, pp. 1067-1069, Aug 1998.
- [19] E. S. Bjorlin, B. Riou, A. Keating, P. Abraham, Y. J. Chiu, J. Piprek, and J. E. Bowers, "1.3- μm vertical-cavity amplifier," *IEEE Photonics Technology Letters*, vol. 12, pp. 951-953, Aug 2000.
- [20] E. S. Bjorlin, T. Kimura, and J. E. Bowers, "Carrier-confined vertical-cavity semiconductor optical amplifiers for higher gain and efficiency," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 9, pp. 1374-1385, Sep-Oct 2003.
- [21] F. Marino and S. Balle, "Experimental study of a broad area vertical-cavity semiconductor optical amplifier," *Optics Communications*, vol. 231, pp. 325-330, Feb 15 2004.

CHAPTER 3

Analysis of the Transverse Leaky Modes of Large-area Antiresonant Reflecting Optical Waveguide Vertical Cavity Surface Emitting Lasers

In this chapter, the method to effectively suppress the higher-order transverse modes of ARROW VCSELs is explored. The model to analyze the optical field in the ARROW structure and the complex rate equation model for large-area VCSELs is described. Using these models, the characteristics of the transverse leaky cavity modes in ARROW VCSELs are investigated. The mechanism of higher-order transverse modes excitation and its prevention are the focus of the study. It is found that the suppression of high-order transverse leaky modes in ARROW VCSELs can be deteriorated by the influence of spatial hole burning and thermal lensing effects. On the other hand, a new design-rule is proposed to deduce the optimum dimensions of ARROW so that the suppression of high-order transverse leaky modes can be enhanced. Furthermore, the turn-on transient response of ARROW VCSELs is investigated. It is found that the radiation loss has significant influence on the built-up time of the first-order transverse leaky mode.

3.1 Introduction

Recently, extensive studies have been concentrated on the modal characteristics of ARROW devices, because ARROW is shown as a good solution for the realization of high-power single-mode operation of large diameter VCSELs. Due to the anti-resonant characteristics of ARROW, the radiation loss of the fundamental transverse leaky mode can be very small while the radiation losses of the high-order transverse leaky modes remained fairly large. This is because of the anti-resonant characteristics of ARROW [1-3]. Hence, ARROW structures are employed to suppress the excitation of high-order transverse leaky modes in VCSELs, especially for those with large core diameter.[4] However, it is observed from experiments that high-order transverse leaky modes can still be excited in ARROW VCSELs under pulsed and continuous wave (CW) operation[4]. This implies that the cold-cavity simulations [3-5] have underestimated the influence of spatial hole burning (SHB) and thermal lensing effects on the excitation of high-order transverse modes. On the other hand, the available above-threshold models of multimode ARROW lasers, in which only the effects of the current injection profile and SHB-induced focusing/defocusing are taken into consideration, were developed for planar structures [6, 7]. However, a self-consistent electro-opto-thermal model for multimode cylindrical ARROW VCSELs is lacking. Therefore, it is necessary to develop a more accurate above-threshold model to investigate the multi-leaky-mode characteristics of ARROW VCSELs.

In the conventional design of ARROW VCSELs, the dimension of ARROW is often selected to minimize the radiation loss of the fundamental transverse leaky mode [4]. This is because if the radiation loss can be minimized in

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

ARROW VCSELs, the corresponding threshold current (output power) can be further decreased (increased). However, large radiation loss margin between the fundamental and first-order transverse leaky modes may not be guaranteed for this design consideration [5]. As a result, high-order transverse leaky modes in ARROW VCSELs with large core diameter can still be excited by SHB and thermal lensing effects. Therefore, it is required to deduce a different design-rule to calculate the optimum dimension of ARROW for better suppression of high-order transverse leaky modes.

In gain- or index- guided VCSELs, the turn-on transient response of the transverse modes is mainly affected by SHB through the time variation of modal gain. However, the transient competition of leaky modes in ARROW VCSELs is dependent on the corresponding modal gain and radiation loss. Hence, it is expected that the turn-on transient response of ARROW VCSELs is different to that of gain- or index- guided VCSELs. If multimode characteristics of ARROW VCSELs are used as the light sources of high-speed multimode data links [8], it is necessary to investigate the turn-on transient response of ARROW VCSELs.

In the following section, a self-consistent model, with SHB of carrier concentration and thermal lensing effects taken into consideration, is developed to analyze the above threshold characteristics of ARROW VCSELs. Exact calculation of transverse leaky modes inside the cylindrical ARROW is also performed. Hence, the steady-state characteristics of ARROW VCSELs obtained from the experiments [4] can be explained. Furthermore, a new design rule is proposed to deduce the optimum dimension of ARROW structure so that

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

Figure 3.1 Schematic of an ARROW VCSEL

the suppression of high-order transverse leaky modes can be enhanced in large aperture ARROW VCSELs. Turn-on transient response of ARROW VCSELs is also investigated. It can be shown that the long built-up time of the first-order transverse leaky mode is due to the presence of radiation loss.

3.2 Modeling large-area ARROW VCSELs

Effective index method has been widely used in the analysis of the modal characteristics of cylindrical VCSELs [3],[10]. In fact, it has been shown that effective index method is sufficient to deduce the transverse field profiles in VCSELs [15]. Therefore in this study, effective index method is also used to calculate the transverse optical fields of ARROW VCSELs. Figure 3.1 shows the schematic of an ARROW VCSEL used in our analysis. The low-index core

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

region (with diameter d_1) is surrounded by two reflectors, which are the first and second cladding layers, with a thickness s of and d_2 , respectively.

The transverse optical field of the ARROW structure can be calculated from the following simplified Helmholtz equation using effective index method in polar coordinates [9]:

$$\frac{\partial^2 \Psi}{\partial r^2} + \frac{1}{r} \frac{\partial \Psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Psi}{\partial \phi^2} + \zeta^2 \Psi = 0 \quad , \quad (3.1)$$

where Ψ is the optical field, r and ϕ are the transverse and azimuthally directions, respectively. ζ is a variable related to the propagation constant and refractive indices.

In this study, a field-transfer matrix method is used to solve the optical field profiles as well as the radiation losses of the corresponding transverse cavity modes of the ARROW VCSELs. The details of using this method to analyze ARROW structure can be found in [5].

Without the inclusion of SHB and thermal effects consideration, the four lowest leaky transverse cavity modes of the waveguide (i.e. LM_{01} , LM_{11} , LM_{02} , LM_{12}) are calculated and the field profiles are plotted in Figure 3.2. It is found for the fundamental transverse leaky cavity mode (i.e. LM_{01}), the field intensity in the cladding region (i.e. $r > d_1/2$) is minimized compared to the other modes, so that it suffers minimum radiation loss and is enhanced. The other higher-order modes are all suffering large radiation losses, and LM_{02} and LM_{12} suffer much greater loss than LM_{11} . Therefore in our investigations to ARROW VCSELs, only the lowest two modes (i.e. LM_{01} and LM_{11}) are involved. The

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

Figure 3.2 Normalized optical field intensity profile of LM_{01} , LM_{11} , LM_{02} , LM_{12}

other higher order modes are not significant enough to influence the laser characteristics due to ARROW's suppression to them, thus are neglected in the study.

Furthermore, due to the symmetric geometry of the device along the emission direction, the azimuthal degree of freedom of the transverse leaky modes has to be taken into account. This can be done by attributing each LM_{m1} mode (where $m = 0$ or 1) a cosine (LM_{m1}^c) and a sine (LM_{m1}^s) azimuthal dependence [10]. The transverse field ψ_{m1}^i and the transverse propagation coefficient β_{m1}^i can be calculated from the scalar Helmholtz equation derived from (3.1), and expressed as

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

$$\left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + n_0^2 k_0^2 - (\beta_{m1}^i)^2 \right) \psi_{m1}^{'i} = 0, \quad (3.2)$$

where $i = c$ or s , n_0 is the refractive index profile of the ARROW, $k_0 (= 2\pi/\lambda)$ is the wave factor, and λ is the free-space wavelength. If the refractive index of the ARROW along the azimuthal direction ϕ is assumed to be uniform, the profile of the transverse field with cosine and sine azimuthal dependence, $\psi_{m1}^{'c}$ and $\psi_{m1}^{'s}$, can be expressed as

$$\begin{aligned} \psi_{m1}^{'c} &= (E^+ H_v^{(1)}(\beta_{m1}^{'c} r) + E^- H_v^{(2)}(\beta_{m1}^{'c} r)) \cos(m\phi) \\ \psi_{m1}^{'s} &= (E^+ H_v^{(1)}(\beta_{m1}^{'s} r) + E^- H_v^{(2)}(\beta_{m1}^{'s} r)) \sin(m\phi) \end{aligned} \quad (3.3)$$

where E^+ (E^-) is the positive (negative) traveling field amplitude along the transverse direction, and $H_v^{(1)}$ ($H_v^{(2)}$) is the v^{th} -order Hankel function of the first (second) kind. It must be noted that in the absence of SHB and thermal lensing effects, $n_0 = n_b'$, where n_b' is the built-in refractive index profile of the ARROW. However, due to the influence of SHB and thermal lensing effects, n_0 has to be rewritten as $n_0^2 = n_b^2(r) + \Delta\epsilon(r, \phi)$, where n_b is the variation of built-in refractive index profile and $\Delta\epsilon$ is a small perturbation of material permittivity along the transverse and azimuthal directions. In a strong guiding device like ARROW, the variation of the transverse field ($\Delta\psi_{m1}^i$) and the propagation coefficient ($\Delta\beta_{m1}^i$) caused by spatial-hole-burning and thermal effects will be less than 10% [11]. Therefore, the small variation of $\psi_{m1}^{'i}$, $\Delta\psi_{m1}^i$, and that of $\beta_{m1}^{'i}$, $\Delta\beta_{m1}^i$ can be estimated by first-order perturbation method [11]:

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

$$\Delta\psi_{m1}^i = \frac{1}{\int_0^{2\pi\infty} \int_0^\infty |\psi_{m1}'^i(r, \phi)|^2 r dr d\phi} \quad (3.4)$$

$$\times \sum_{n \neq m} \frac{k_o^2 \int_0^{2\pi\infty} \int_0^\infty \psi_{n1}'^{i*}(r, \phi) \Delta\epsilon(r, \phi) \psi_{m1}'^i(r, \phi) r dr d\phi}{\beta_{m1}'^2 - \beta_{n1}'^2} \psi_{n1}'^i(r, \phi)$$

$$\Delta\beta_{m1}^i = \frac{k_o^2 \int_0^{2\pi\infty} \int_0^\infty \psi_{m1}'^{i*}(r, \phi) \Delta\epsilon(r, \phi) \psi_{m1}'^i(r, \phi) r dr d\phi}{2\beta_{m1}'^i \int_0^{2\pi\infty} \int_0^\infty |\psi_{m1}'^i(r, \phi)|^2 r dr d\phi}, \quad (3.5)$$

where the superscript “*” represents the complex conjugate. Hence, the resultant transverse field, ψ_{m1}^i , and transverse propagation coefficient, β_{m1}^i , can be written as $\psi_{m1}^i = \psi_{m1}'^i + \Delta\psi_{m1}^i$ and $\beta_{m1}^i = \beta_{m1}'^i + \Delta\beta_{m1}^i$, respectively.

The photon rate equations that describe the competition of the transverse modes inside an ARROW VCSEL can be written as [12]

$$\frac{dS_{m1}^i}{dt} = \nu_g \left(\Gamma_z \langle g_{m1}^i \rangle - \alpha_{m1}^i - \zeta_{m1}^i \right) S_{m1}^i + \beta_{sp} \Gamma_z B_{sp} \langle N \rangle^2, \quad (3.6)$$

where S_{m1}^i is the photon density of the LM_{m1}^i , t is time, Γ_z is the confinement factor along the longitudinal direction, ν_g is the group velocity, B_{sp} is the bimolecular recombination coefficient, β_{sp} is the spontaneous emission factor and $\alpha_{m1}^i (=2 \times \text{Im}(\beta_{m1}^i)/k_0)$ is the radiation loss. The total cavity loss, $\zeta_{m1}^{c,s}$, of LM_{01} and LM_{11} has included mirror and absorption losses. In (3.6), it is assumed that the polarization mechanism of ARROW VCSEL is mainly dependent on the polarization and gain/loss anisotropies inside the laser cavity, so that the influence of carrier spin effects [13] is ignored in the calculation. The modal gain, $\langle g_{m1}^i \rangle$, is given by

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

$$\langle g_{m1}^i \rangle = \frac{\int_0^{2\pi} \int_0^\infty g(N) |\psi_{m1}^i(r, \phi, t)|^2 r dr d\phi}{\int_0^{2\pi} \int_0^\infty |\psi_{m1}^i(r, \phi, t)|^2 r dr d\phi}, \quad (3.7)$$

where $g(N) = a_N \log[N(r, \phi, t)/N_t]$, N is the carrier concentration, N_t is the transparent carrier density and a_N is the gain coefficient, which is assumed to be a constant in this study. The temperature dependence of a_N is ignored to simplify our model, as this study is focused on the influence of ARROW structure on the excitation of higher-order transverse modes of VCSELs. $\langle N \rangle$ in (3.6) has the similar definition as $\langle g_{m1}^i \rangle$. It should be noted there are no coupling terms between different transverse modes in (3.6). This is because the geometry of the VCSELs is assumed to be symmetric along the propagation direction. As a result, the mathematical model for VCSELs will not produce asymmetric solutions so that the profiles of the transverse modes should be orthogonal. Based on this assumption, we have ignored the power exchange among the transverse modes in the derivation of equation (3.6). The influence of non-orthogonal profile of the transverse modes can be taken into consideration by introducing unsymmetrical laser cavity. However, this is out of the scope of this study.

The output power of the ARROW VCSEL is calculated by $P_{m1}^i = hf\nu_g (1 - r_{\text{eff}}^2) AS_{m1}^i$, where h is the Planck's constant, f is the lasing frequency, r_{eff} is the effective reflectivity of the Bragg reflectors and $A (= \pi d_1^2/4)$ is the area of the core region.

The rate equation that accounts for the transverse and azimuthal variation of carrier concentration, $N(r, \phi, t)$, can be expressed as [10]

$$\begin{aligned} \frac{\partial N(r, \phi, t)}{\partial t} = & D \left[\frac{1}{r} \frac{\partial N}{\partial r} + \frac{\partial^2 N}{\partial r^2} \right] + D \frac{1}{r^2} \frac{\partial^2 N}{\partial \phi^2} + \frac{J(r, \phi, t)}{ed_a} - \frac{N}{\tau_N} \\ & - g(N) \left(a_{01} |\psi_{01}(r, t)|^2 S_{01} + a_{11}^c |\psi_{11}^c(r, t) \cos \phi|^2 S_{11}^c + a_{11}^s |\psi_{11}^s(r, t) \sin \phi|^2 S_{11}^s \right), \end{aligned} \quad (3.8)$$

where D is the diffusion coefficient, e ($= 1.602 \times 10^{-19}$ C) is the electron charge, d_a is the thickness of active layer, and τ_N is the carrier lifetime.

$a_{m1}^i = \pi v_g \Gamma R^2 \int_0^{2\pi} \int_0^\infty |\psi_{m1}^i(r, \phi, t)|^2 r dr d\phi$, where $R = d_1/2 + s + d_2$. In our study, it

is assumed that $J(r, \phi, t)$ is uniformly injected into the core region through a transparent electrode with same diameter as the core region. Hence, the distribution of J can be approximated by [14]

$$J(r, \phi, t) = \begin{cases} J_e(t) & r \leq d_1/2 \\ J_e(t) \exp(-(r - d_1/2)/r_o) & r > d_1/2 \end{cases}, \quad (3.9)$$

where J_e denotes the current density at the edge and within the contact area ($r \leq d_1/2$), and r_o is the effective diffusion length of the injection current. To simplify the calculation of (3.8), we expand N in a Fourier series expansion [10]

$$N(r, \phi, t) = \sum_{k=0}^{\infty} [N_{ck}(r, t) \cos(k\phi) + N_{sk}(r, t) \sin(k\phi)]. \quad (3.10)$$

where N_{ck} (N_{sk}) is the coefficient for the cosine (sine) series.

Substituting (3.10) into (3.8) and integrating over ϕ , we obtain

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

$$\begin{aligned} \frac{\partial N_{c0}(r,t)}{\partial t} = D \left[\frac{1}{r} \frac{\partial N_{c0}}{\partial r} + \frac{\partial^2 N_{c0}}{\partial r^2} \right] - \frac{N_{c0}}{\tau_N} + \frac{J(r,t)}{ed_a} \\ - g(N) \left(a_{01} |\psi_{01}(r,t)|^2 S_{01} + \frac{1}{2} a_{11}^c |\psi_{11}^c(r,t)|^2 S_{11}^c + \frac{1}{2} a_{11}^s |\psi_{11}^s(r,t)|^2 S_{11}^s \right) \end{aligned} \quad (3.11)$$

Again, by substituting (3.10) into (3.8) with the multiplication of $\cos(q\phi)$ (q is an arbitrary integer), and integrating over ϕ , gives

$$\begin{aligned} \frac{\partial N_{cq}(r,t)}{\partial t} = D \left[\frac{1}{r} \frac{\partial N_{cq}}{\partial r} + \frac{\partial^2 N_{cq}}{\partial r^2} \right] - \frac{D}{r^2} q^2 N_{cq} - \frac{N_{cq}}{\tau_N} \\ - g(N) \cdot \frac{1}{2} \delta_{2m,q} \left(a_{11}^c |\psi_{11}^c(r,t)|^2 S_{11}^c - a_{11}^s |\psi_{11}^s(r,t)|^2 S_{11}^s \right) \end{aligned} \quad (3.12)$$

where $\delta_{2m,q} = 1$ if and only if $2m=q$, otherwise $\delta_{2m,q} = 0$. Substituting (3.10) into (3.8) with the multiplication of $\sin(q\phi)$, and integrating over ϕ , gives

$$\frac{\partial N_{sq}(r,t)}{\partial t} = D \left[\frac{1}{r} \frac{\partial N_{sq}}{\partial r} + \frac{\partial^2 N_{sq}}{\partial r^2} \right] - \frac{D}{r^2} q^2 N_{sq} - \frac{N_{sq}}{\tau_N}. \quad (3.13)$$

If the initial distribution of N is assumed to be uniform over ϕ , then $N_{cq}(r, t = 0) = N_{sq}(r, t = 0) = 0$ as well as $N_{cq}(r, t = 0) = N(r, t = 0)$ can be deduced. These imply that $N_{sq} = 0$ for all q and $N_{cq} = 0$ for all q except $q = 0$ and $q = 2$. Hence, (3.8) can be simplified after putting $N = N_{c0} + N_{c2} \cos(2\phi)$ back into it.

In the operation of large-area ARROW VCSELs, spatial hole burning (SHB) and thermal lensing effects are significant and they are believed to be the main cause of the multi-transverse-mode output. SHB and thermal lensing lead to a distortion of the carrier concentration distribution and temperature profile shape and thus result in significant refractive index change along the transverse direction. In order to study the influence of SHB and thermal effects on the

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

characteristics of large-area ARROW VCSELs, it is necessary to include the consideration of the refractive index changes due to carrier and thermal effects in the model of ARROW VCSELs.

The carrier-induced refractive index change, δn_N , can be expressed as [15]

$$\delta n_N = -\alpha_H \frac{\lambda}{4\pi} \Gamma \frac{\partial g}{\partial N} \Delta N, \quad (3.14)$$

where α_H is the linewidth enhancement factor, ΔN is the change of carrier concentration and $\partial g / \partial N$ is the differential gain.

The influence of thermal lensing can also be included into the model by solving the heat equation using Green's model [16]. The temperature varies along the active layer, $T(r, t)$, can be written as

$$T(r, t) = T_0 + \frac{4}{HW^2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{A_{mn}}{J_0^2(L_n W)} \sin(K_m z_a) J_0(L_n r), \quad (3.15)$$

where T_0 is the background temperature, z_a is the distance between the heatsink and active layer, H is the height of the VCSELs, $W = d_1/2 + s + d_2$, J_0 is the zeroth-order Bessel function of the first kind, and

$$A_{mn} = \int_0^t \int_0^H \int_0^W \frac{k_i}{\lambda_i} \sin(K_m z) J_0(L_n r) r Q(r, z) \times \exp[k_i (K_m^2 + L_n^2)(u - t)] du dr dz \quad (3.16)$$

$$\begin{aligned} K_m &= \frac{(2m-1)\pi}{2W}, \quad m = 1, 2, 3, \dots \\ L_n &= \frac{\eta_n}{d_1}, \quad n = 1, 2, 3, \dots \end{aligned} \quad (3.17)$$

where $Q(r, z)$ is the heat density, λ_i is the thermal conductivity, k_i is the thermal diffusivity and η_n are the roots of $J_1(L_n w) = 0$. It must be noted that the injection

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

current density, J , is independent of ϕ , so it is reasonable to assume that $T(r,t)$ is uniformly distributed over the ϕ direction. Thermal induced refractive index variation, δn_T , inside the active layer can then be expressed in term of the temperature change as

$$\delta n_T(r,t) = \frac{\partial n}{\partial T} \Delta T(r,t), \quad (3.18)$$

where $\partial n / \partial T$ is the heat induced index change coefficient and ΔT is the change of temperature from background. Hence, the influence of SHB and thermal lensing on the variation of ψ_{m1}^i and β_{m1}^i can be calculated by (3.4) and (3.5) with $n_0 = n_B + \delta n_N + \delta n_T$ where n_B is the background index profile of ARROW. Note that the temperature dependency of the parameters a_N , N_t and τ_N has been ignored in order to facilitate our study. Therefore thermal rollover of the light-current curve is not included in our model. This approximation is still valid because the excitation of high-order transverse modes is mainly dependent on the effective refractive index profile of the ARROW VCSEL.

A self-consistent iteration process is used to calculate the SHB and thermal lensing simultaneously in the laser model. The process starts with the estimation of the transverse optical field profiles without the consideration of SHB and thermal lensing effects. These initial transverse field profiles will then be used to calculate the corresponding modal gain as indicated in (3.7). In addition, photon density and the profile of carrier concentration of the devices can be calculated by using (3.6) and (3.8). Using (3.14), the non-uniform distribution of carrier-induced index change, δn_N , can then be calculated from the change of carrier concentration profile. The temperature profile of the

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

devices can also be calculated from (3.15) with the non-uniform injection of current density taken into consideration. Heat induced index change of the devices can also be obtained from (3.18) from the change of temperature profile. As a result, we can obtain the total refractive index change due to the carrier and heat induced refractive index change.

The transverse optical field profiles will then be re-calculated so that the influence of SHB and thermal lensing effects can be taken into consideration. The new profile of transverse optical fields will then be used to re-calculate the photon density, non-uniform distribution of the carrier concentration and heat. The above calculations will then be repeated until the difference in the variation of refractive index change of the two subsequent iterations is less than some predefined value.

3.3 Analysis of the transverse leaky modes

With the models introduced in the preceding section, a comprehensive study of the transverse leaky modes of ARROW VCSELs is conducted in this section. The parameters used in the calculation are listed in Table 3.1. These parameters are selected to be comparable with the ARROW VCSEL reported in [3] and [4] to make the simulation realistic.

Table 3.1**Device and Material Parameters**

Symbol	Value	Meaning of the Symbol
λ	0.98 μm	free space wavelength
v_g	$83.3 \times 10^8 \text{ cm/s}$	group velocity
B_{sp}	$1 \times 10^{-10} \text{ cm}^3/\text{s}$	bimolecular recombination coefficient
β_{sp}	1×10^{-5}	spontaneous emission factor
N_t	$1.5 \times 10^{18} \text{ cm}^{-3}$	transparent carrier density
a_N	$1.5 \times 10^3 \text{ cm}^{-1}$	gain coefficient
$\zeta_{01}^{c,s}$	55 cm^{-1}	total cavity loss of LM ₀₁
$\zeta_{11}^{c,s}$	60 cm^{-1}	total cavity loss of LM ₁₁
D	1 cm^2/s	diffusion coefficient
q	$1.602 \times 10^{-19} \text{ C}$	electron charge
d	$0.1 \times 10^{-4} \text{ cm}$	thickness of active layer
τ_N	1 ns	carrier lifetime
r_o	1.5 m	effective diffusion length of the injection current
$\partial n / \partial T$	$\sim 3 \times 10^{-4} \text{ K}^{-1}$	heat induced index change coefficient

It should be noted from the above table, LM₁₁ has a higher cavity loss than that of LM₀₁. This is because LM₁₁ has a large portion of the field-intensity residing inside the cladding region in which high absorption loss is assumed and the influence of absorption losses are taken into account into the cavity losses of the two transverse modes.

3.3.1 Steady-State Above-Thresholds Analysis of ARROW VCSELs

The steady-state characteristics of ARROW VCSEL with dimensions same as that reported in [4] are studied. In the calculation, d_1 , s , and d_2 are set to 12 μm , 2.4 μm and 6 μm , respectively. The built-in index step, Δn_b , is set to 0.05, with $n'_{b1} = n'_{b3} = 3.3$ and $n'_{b2} = n'_{b4} = 3.3 + \Delta n_b$. Other parameters used in the

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

calculation can be found in Table 3.1. The steady-state characteristics of the ARROW VCSEL are investigated through the study of light-current (L-I) curve, gain margin, radiation loss margin and side mode suppression ratio. The gain margin (GM) is defined as

$$GM = \frac{1}{2} \sum_{i=c,s} \left\{ \left(\langle g_{01}^i \rangle - \alpha_{01}^i - \zeta_{01}^i \right) - \left(\langle g_{11}^i \rangle - \alpha_{11}^i - \zeta_{11}^i \right) \right\}, \quad (3.19)$$

which measures the difference in modal gains between the fundamental (LM₀₁) and first-order (LM₁₁) transverse modes. The radiation loss margin (RLM) is defined as

$$RLM = \frac{1}{2} \sum_{i=s,c} \left(\alpha_{01}^i - \alpha_{11}^i \right), \quad (3.20)$$

which indicates the differences in radiation losses between LM₀₁ and LM₁₁.

Side mode suppression ratio, SMSR, is given by

$$SMSR = 10 \log_{10} \left\{ \left(S_{01}^s + S_{01}^c \right) / \left(S_{11}^s + S_{11}^c \right) \right\}. \quad (3.21)$$

Figure 3.3 shows the calculated (a) light-current (L-I) curve, (b) GM, (c) RLM, and (d) SMSR of the ARROW VCSEL. In the figures, the dash-dotted and solid lines represent the cases with and without thermal lensing effects taken into consideration, respectively. It is observed that for the case where only SHB of carrier concentration is considered, VCSEL shows single-mode emission for the injection level up to $\sim 2.8 \times$ threshold, which corresponds to an output power of ~ 10 mW. However, with the inclusion of thermal lensing effects, ARROW VCSEL exhibits multimode operation for the injection level $> 1.8 \times$ threshold, with a maximum single-mode output power of ~ 4.5 mW. It is reported in [4] that ARROW VCSELs with $12\text{-}\mu\text{m}$ -diameter core have a threshold current varies between 10 and 12 mA. However, multimode operation

Figure 3.3 Steady-state characteristics of a $12\text{-}\mu\text{m}$ -core-diameter ARROW VCSEL. (a) L-I curve, (b) GM, (c) RLM, and (d) SMSR

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

was observed at $\sim 2 \times$ threshold, with a maximum single mode output power in the range of 4 – 5 mW. These results agreed well with our simulation results. It is also observed that the L-I curve given in Figure 3.3a agreed quantitatively with that given in Fig. 9 of [4].

Furthermore, the corresponding values of GM and RLM reduce over 30 cm^{-1} and 10 cm^{-1} , respectively, under the influence of thermal lensing effects. In addition, SMSR reduces by 10 dB at small injection level, and decreases more than 20dB when higher order transverse modes are excited.

In order to explain the excitation mechanism of high-order transverse leaky modes in $12 \text{ }\mu\text{m}$ core diameter ARROW VCSELs under CW operation, Figure 3.4 plots the (a) fundamental field-intensity, (b) first-order field-intensity, (c) refractive index profile $\delta n_0 + \delta n_T$, (d) N_{c0} , (e) N_{c2} , and (f) heat profile ΔT versus r for injection current equal to 0.8, 1, 1.25, 1.5, 1.8, $2.25 \times$ threshold. From Figure 3.4a and b, it is observed that the increase of injection current results in the focusing of the fundamental and first-order transverse leaky modes towards the center. As a result, the modal gain (radiation loss) of first-order transverse mode is greatly enhanced (reduced), causing the onset of multimode operation at high injection level. Focusing of transverse leaky modes is due to the increase in refractive index inside the core region. The variation of refractive index profile along the core region can be attributed to the non-uniform distribution of carrier concentration and heat. However, it is observed from Figure 3.4c-f that the profile of refractive index follows mostly the heat distribution. Therefore, it is shown that thermal lensing effects dominate over the SHB of carrier concentration.

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

Figure 3.4 Steady-state characteristics of a 12- μm -core-diameter ARROW VCSEL. (a) Field-intensity profile of LM_{01}^i , (b) field-intensity of LM_{11}^i , (c) transverse refractive-index change, (d) N_{c0} ($\times 10^{18} \text{ cm}^{-3}$), (e) N_{c2} ($\times 10^{18} \text{ cm}^{-3}$), and (f) temperature rise along the transverse direction in active region (K). The arrows indicate the change in profiles with the increase of injection current.

3.3.2 New Design Rule for ARROW VCSELs

In the design of ARROW VCSELs, dimensions of the cladding layers are often selected such that the radiation loss of the fundamental transverse mode is the minimum. However, this design consideration does not guarantee a large RLM. As a result, excitation of high-order transverse leaky modes may still

occur in ARROW VCSELs by the influence of SHB and thermal lensing effects. Therefore, a new design-rule is proposed to improve the above threshold performance of ARROW VCSELs. The design-rule can be explained as follows: for a given core diameter d_1 , the dimensions of the cladding layers s and d_2 of ARROW are optimized for minimum radiation loss of the fundamental transverse leaky mode. Then, the value of s is allowed to increase so that the corresponding value of RLM is increased but the radiation loss of the fundamental transverse leaky mode still remained at a low value.

Figure 3.5 Radiation loss of the four lowest loss leaky modes plotted against the first cladding layer width s with $d_1 = 12 \mu\text{m}$ and $d_2 = 3.9 \mu\text{m}$. The four leaky modes LM_{01} , LM_{11} , LM_{02} , LM_{12} are identified by solid, dashed-dotted, dotted, and dashed lines, respectively

This design-rule can be illustrated by the design of a 12- μm core diameter ARROW VCSEL for the enhancement of side-mode suppression. It can be shown that the values of s and d_2 for minimum radiation loss ($\sim 0.079\text{cm}^{-1}$) of the fundamental transverse leaky mode are $\sim 1.28\text{ }\mu\text{m}$ and $3.9\text{ }\mu\text{m}$, respectively [5]. Figure 3.5 plots the radiation losses of the four lowest radiation losses transverse modes for $d_1=12\text{ }\mu\text{m}$, $d_2=3.9\text{ }\mu\text{m}$ and $\Delta n_b = 0.05$. It's noted that when $s = 2.46\text{ }\mu\text{m}$, the new RLM is $\sim 14\text{ cm}^{-1}$ and the radiation loss of the fundamental mode is $\sim 0.45\text{ cm}^{-1}$. If the value of s is further increased, the radiation loss of the fundamental mode will increase to 4 cm^{-1} . In Figure 3.6, the field-intensity profile of the four leaky modes is also plotted with $s = 2.46\text{ }\mu\text{m}$. This new design-rule can be used to evaluate the optimum dimensions of the ARROW for single-mode emission because the RLM is maximized but the radiation loss of the fundamental mode is only slightly increased.

Figure 3.6 Field-intensity profile of leaky modes (a) LM_{01} (solid line) and LM_{02} (dotted line) and (b) LM_{11} (dashed-dotted line) and LM_{12} (dashed line), with $d_1 = 12\text{ }\mu\text{m}$, $s = 2.46\text{ }\mu\text{m}$, and $d_2 = 3.9\text{ }\mu\text{m}$

Figure 3.7 Field-intensity profile of LM_{11} in (a) a conventional ARROW VCSEL and (b) an ARROW VCSEL designed based on the new approach

The enhancement of RLM can be explained by the field-intensity profile of first-order transverse leaky mode. Figure 3.7 plots the field-intensity profile of the first-order transverse mode using (a) $s = 2.4 \mu\text{m}$ and $d_2 = 6 \mu\text{m}$ and (b) $s = 2.46 \mu\text{m}$ and $d_2 = 3.9 \mu\text{m}$. It is noted that in Figure 3.7b, the first-order transverse mode experiences a much higher radiation loss. This is because a large portion of the first-order transverse leaky mode is distributed within the second cladding layer (beyond the current confinement region). As a result, RLM is improved in the new design as the corresponding first-order transverse leaky mode has suffered a much higher absorption loss than that of the conventional design.

Figure 3.8 compares the performance of the two design methods of ARROW VCSEL in terms of (a) L-I curve and (b) SMSR. In the figure, the solid line (dash-dotted line) denotes device designed using the new approach (conventional approach). It is observed that the new design is capable of

Figure 3.8 (a) L-I curve and (b) side-mode suppression ratio for ARROW VCSEL designed using conventional approach (dash-dotted line) and new approach (solid line).

delaying the onset of higher order transverse mode from 1.8 to $2.3 \times$ threshold. Furthermore, the maximum single-mode power is improved from ~ 4 mW to more than ~ 7 mW (i.e., more than 75% of improvement). SMSR is also increased by more than ~ 6 dB under low injection current when compare with the conventional design.

Figure 3.9a plots the radiation losses of the four transverse leaky modes ($LM_{01}^i, LM_{11}^i, LM_{02}^i$ and LM_{12}^i) versus s for $d_1 = 12 \mu\text{m}$, $d_2 = 6 \mu\text{m}$, and $\Delta n_b = 0.05$ obtained from the transfer matrix method [17]. It is found that the radiation loss of fundamental mode and the corresponding RLM are equal to $\sim 0.385 \text{ cm}^{-1}$ and $\sim 3 \text{ cm}^{-1}$, respectively, if $s = 2.4 \mu\text{m}$ is used instead of the value for minimum radiation loss of the fundamental transverse leaky mode. On the other hand, the radiation losses of the $8 \mu\text{m}$ core diameter ARROW VCSEL with $d_2 = 4 \mu\text{m}$ and $\Delta n_b = 0.05$ are also analyzed, as shown in Figure 3.9b. In this case, the radiation loss of fundamental mode and the corresponding RLM are found to be $\sim 2 \text{ cm}^{-1}$

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

and $\sim 13 \text{ cm}^{-1}$, respectively, for $s = 2.4 \text{ }\mu\text{m}$. It is shown that the RLM of $8 \text{ }\mu\text{m}$ and $12 \text{ }\mu\text{m}$ ARROW VCSELs has been improved from 7 cm^{-1} to 13 cm^{-1} and 1 cm^{-1} to 3 cm^{-1} , respectively. It should be noted that the RLM value of the $12 \text{ }\mu\text{m}$ device is relatively smaller than that of the $8 \text{ }\mu\text{m}$ device. This explains the reason why the $12 \text{ }\mu\text{m}$ core diameter ARROW VCSEL exhibits multimode operation at high injection level while the $8 \text{ }\mu\text{m}$ core diameter ARROW VCSEL maintains single-mode operation until the thermal rollover [4].

However, the high radiation loss of the fundamental transverse leaky mode in the $8\text{-}\mu\text{m}$ device ($\sim 2 \text{ cm}^{-1}$) results in a relatively large threshold current, which is in good agreement with the observation reported in [4]. It must be noted that the value of d_2 used in Figure 3.9a is obtained from the planar approximation [3], however, the value of d_2 used in Figure 3.5 is calculated from our more accurate design model [5]. Hence, the value of d_2 given in Figure 3.9a is not really optimized for the devices.

Figure 3.9 Radiation loss of the four lowest loss leaky modes plotted against s , with (a) $d_1 = 12 \mu\text{m}$ and $d_2 = 6 \mu\text{m}$ and (b) $d_1 = 8 \mu\text{m}$ and $d_2 = 4 \mu\text{m}$

3.3.3 Turn-On Transient Response of ARROW VCSELs

Figure 3.10 plots the turn-on transient response of a 12 μm core diameter ARROW VCSEL (with $s = 2.4 \mu\text{m}$, $d_2 = 6 \mu\text{m}$ and $\Delta n_b = 0.05$). The laser starts at zero and is modulated with a step current density with a magnitude of $\sim 3 \times$ threshold. The influence of thermal effect is ignored because the thermal lifetime of lasers is much longer than the oscillation period of photon density and carrier concentration.

It is observed from Figure 3.10d that during the first transient period of 0.6 ns, N_{e0} built-up to about $2.3 \times 10^{18} \text{ cm}^{-3}$ inside the core region, thereby exciting the fundamental transverse mode due to the increase in modal gain. However, the excitation of fundamental transverse leaky mode causes SHB of carrier concentration at the center of the core region. It is observed that SHB is established at time ~ 0.9 ns, and the first-order transverse leaky mode is excited at around 1.6 ns.

As shown in Figure 3.10a, the two transverse leaky modes exhibit anti-phase oscillation from 1.6 ns onwards. The anti-phase oscillation of fundamental and first-order transverse modes is due to the gain-sharing mechanism inside the core region. The phenomenon of anti-phase oscillation is also observed in index-guided VCSELs with a large core diameter[10]. However, the prolonged delay in the excitation of first-order transverse mode is unique in ARROW VCSELs.

Figure 3.10 Turn-on transient response of (a) output power, (b) net modal gain, (c) radiation loss, (d) N_{c0} and (e) N_{c2} . The solid and dash-dotted lines represent LM_{01} and LM_{11} , respectively.

It must be noted that the radiation losses of the transverse leaky modes in ARROW VCSELs are affected by the SHB of carrier concentration. Before 0.8 ns, the corresponding radiation loss of the first-order transverse leaky mode is greater than 23 cm^{-1} (instead of $\sim 3.4 \text{ cm}^{-1}$ obtained from cold-cavity simulation). This is because the high carrier concentration inside the core region significantly reduces the refractive index of the core region of the ARROW structure. Between 0.8 ns and 1.6 ns, the SHB of carrier concentration is established, causing the reduction of the first-order radiation loss. Therefore, the corresponding net gain of the first-order transverse leaky mode, defined as $\sum_{i=c,s} \left(\langle g_{11}^i \rangle - \alpha_{11}^i - \zeta_{11}^i \right)$, increases from less than -20 cm^{-1} to 0 cm^{-1} , enabling it to acquire threshold. However, it is noted from Figure 3.10c that the radiation loss of the first-order transverse leaky mode takes longer time to reach a lower value before it can be excited. Therefore, a prolonged delay in the excitation of the first-order transverse leaky mode is observed in ARROW VCSELs. It should be noted that this phenomenon will not occur in gain- or index- guided VCSELs because their transverse modes in these devices have no radiation losses.

3.4 Discussion and Conclusion

Using the above threshold model, the steady state characteristics of 8- μm and 12- μm -core-diameter ARROW VCSELs are investigated and compared with the experimental results [4] in this chapter. It is shown that the reason for 8- μm ARROW VCSEL to exhibit better suppression of high-order transverse leaky modes than that of a 12- μm device (under the influence of SHB and thermal lensing effects) is the large RLM. The RLM values of 12- and 8- μm ARROW

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

VCSELs obtained from the cold-cavity simulation [5] are ~ 3 and $\sim 13 \text{ cm}^{-1}$, respectively. This indicated that the possible method for maintaining single-mode operation in ARROW VCSELs is to increase the value of RLM by compromising with a slightly higher threshold current.

In conclusion, the above-threshold characteristics of ARROW VCSELs are studied by a simple self-consistent model, in which the spatial-hole burning of carrier concentration, optical field intensity and thermal lensing are taken into consideration. It is shown that the excitation of high-order transverse leaky modes in ARROW VCSELs under CW operation is mainly dependent on thermal lensing effects. For the lasers under pulsed operation, the SHB of carrier concentration is the only cause of the excitation of high-order transverse leaky modes. A new design rule is also proposed to obtain the optimum dimension of ARROW VCSELs for better suppression of high-order transverse modes. It can be shown that the new optimum dimension of ARROW has significant improvement in SMSR, and the maximum single-mode power can be improved by more than 75%. The turn-on transient response of ARROW VCSELs is also studied. It is shown that the prolonged delay of the excitation of first-order transverse leaky mode is due to the influence of radiation loss.

REFERENCES

- [1] L. J. Mawst, D. Botez, C. Zmudzinski, and C. Tu, "Antiresonant Reflecting Optical Wave-Guide-Type, Single-Mode Diode-Lasers," *Applied Physics Letters*, vol. 61, pp. 503-505, Aug 3 1992.
- [2] D. Zhou and L. J. Mawst, "Simplified-antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *Applied Physics Letters*, vol. 76, pp. 1659-1661, Mar 27 2000.
- [3] T. W. Lee, S. C. Hagness, D. L. Zhou, and L. J. Mawst, "Modal characteristics of ARROW-type vertical-cavity surface-emitting lasers," *IEEE Photonics Technology Letters*, vol. 13, pp. 770-772, Aug 2001.
- [4] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.
- [5] C. W. Tee and S. F. Yu, "Design and analysis of cylindrical antiresonant reflecting optical waveguide," *Journal of Lightwave Technology*, vol. 21, pp. 3379-3386, Dec 2003.
- [6] L. J. Mawst, D. Botez, R. F. Nabiev, and C. Zmudzinski, "Above-Threshold Behavior of High-Power, Single-Mode Antiresonant Reflecting Optical Wave-Guide Diode-Lasers," *Applied Physics Letters*, vol. 66, pp. 7-9, Jan 2 1995.
- [7] J. C. Chang, J. J. Lee, A. Al-Muhanna, L. J. Mawst, and D. Botez, "Comprehensive above-threshold analysis of large-aperture (8-10 μm) antiresonant reflecting optical waveguide diode lasers," *Applied Physics Letters*, vol. 81, pp. 4901-4903, Dec 23 2002.
- [8] K. H. Hahn, M. R. Tan, Y. M. Houn, and S. Y. Wang, "Large-Area Multitransverse-Mode VCSELs for Modal Noise-Reduction in Multimode Fiber Systems," *Electronics Letters*, vol. 29, pp. 1482-1483, Aug 5 1993.
- [9] C. C. Davis, *Lasers and electro-optics : fundamentals and engineering*. Cambridge ; New York: Cambridge University Press, 1996.
- [10] A. Valle, "Selection and modulation of high-order transverse modes in vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 34, pp. 1924-1932, Oct 1998.
- [11] S. F. Yu and E. H. Li, "Effects of Lateral-Modes on the Static and Dynamic Behavior of Buried Heterostructure DFB Lasers," *IEE Proceedings-Optoelectronics*, vol. 142, pp. 97-102, Apr 1995.

Chapter 3 Analysis of the Transverse Leaky Modes of Large-area ARROW VCSELs

- [12] S. F. Yu, "Polarization selection in birefringent antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 39, pp. 1362-1371, Nov 2003.
- [13] M. Sanmiguel, Q. Feng, and J. V. Moloney, "Light-Polarization Dynamics in Surface-Emitting Semiconductor-Lasers," *Physical Review A*, vol. 52, pp. 1728-1739, Aug 1995.
- [14] N. K. Dutta, "Analysis of current spreading, carrier diffusion, and transverse mode guiding in surface emitting lasers," *Journal of Applied Physics*, vol. 68, pp. 1961-1963, September 1, 1990.
- [15] S. F. Yu, "*Analysis and design of vertical cavity surface emitting lasers*". 1st edition, New York: John Wiley & Son, 2003.
- [16] Y. G. Zhao and J. G. Mcinerney, "Transient Temperature Response of Vertical-Cavity Surface-Emitting Semiconductor-Lasers," *IEEE Journal of Quantum Electronics*, vol. 31, pp. 1668-1673, Sep 1995.
- [17] C. W. Tee, C. C. Tan, and S. F. Yu, "Design of antiresonant-reflecting optical waveguide-type vertical-cavity surface-emitting lasers using transfer matrix method," *IEEE Photonics Technology Letters*, vol. 15, pp. 1231-1233, Sep 2003.

CHAPTER 4

Study of ARROW VCSELs under External Optical Feedback

In this chapter, the effect of external optical feedback on the transient response of ARROW VCSELs is studied. It can be shown that the proper design of ARROW can suppress the excitation of high-order transverse leaky-mode as well as increase the critical feedback strength so that stable high-power single-mode operation of VCSELs can be obtained even under the influence of strong external optical feedback.

4.1 Introduction

The multi-transverse leaky mode characteristics of ARROW VCSELs have been studied in the preceding chapter. It is found that single transverse leaky mode output stability of ARROW VCSELs can be enhanced by the new design approach for the ARROW structure. In this chapter, ARROW VCSELs' output stability under external optical feedback is studied. This is because it is inevitable that optical feedback of light will travel back into the laser cavity in most of the optical communication networks. Linewidth narrowing and broadening, mode-hopping, coherence collapse, and degradation of intensity-noise have been observed experimentally in VCSELs under the influence of

optical feedback [3]. Hence, it is interested to study the transient response of ARROW VCSELs under the influence of optical feedback.

Previous studies of ARROWs have found that the large radiation loss difference between fundamental transverse mode and other high-order modes can minimize the effects of optical feedback on the output transverse mode selection [1]. It is also believed that the reduction of photon lifetime in VCSELs (by increasing the radiation loss of ARROW) but without sacrificing the high reflectivity of distributed Bragg reflectors (DBRs) may reduce the sensitivity of VCSELs to optical feedback [2]. However, these characteristics of ARROW VCSELs have not been explored. In this chapter, the capability of using ARROW to achieve stable high-power single-mode operation in VCSELs under the influence of external optical feedback is investigated.

Figure 4.1 Schematic of an ARROW VCSEL under the influence of external optical feedback

4.2 Numerical Simulations

The schematic of an ARROW VCSEL with an external optical reflector is given in Figure 4.1. It is assumed that the ARROW has a low-index core region of diameter d_1 which is surrounded by two cladding layers of thickness s (1st cladding layer) and d_2 (2nd cladding layer). The refractive indices of the core (n_1), 1st (n_2), 2nd (n_3) and the outer cladding layers (n_4) are 3.3, 3.35, 3.3 and 3.35, respectively. The external reflector is located at some distance away from the p-DBR. The free space lasing wavelength is assumed to be 0.98 μm . Two transverse leaky modes (i.e., LM_{01} and LM_{11}), which have the lowest radiation losses, are only considered in this investigation. This is because the radiation losses of other higher transverse leaky modes are much higher than that of LM_{01} and LM_{11} in ARROW.

The rate equations of photon density, S_m , and phase, ϕ_m , which take into consideration of external optical feedback, can be written as [2]

$$\partial S_m / \partial t = v_g (\Gamma_z \langle g_m \rangle - \alpha_m - \zeta_m) S_m + \beta_{sp} \Gamma_z B_{sp} \langle N \rangle^2 + \text{Ref}_{S,m}(t), \quad (4.1)$$

$$\partial \phi_m / \partial t = \frac{1}{2} \alpha_H v_g \Gamma_z [\langle g_m \rangle - \langle g_{th,m} \rangle] + \text{Ref}_{\phi,m}(t), \quad (4.2)$$

where the subscript $m = 0$ and 1 represent LM_{01} and LM_{11} , respectively, and $\langle \rangle$ is the spatial average. N is the carrier concentration, Γ_z ($=0.06$) is the longitudinal confinement factor, v_g ($=83.3 \times 10^8 \text{ cm/s}$) is the group velocity, B_{sp} ($=1 \times 10^{-10} \text{ cm}^3/\text{s}$) is the bimolecular recombination coefficient, α_H ($=3.0$) is the linewidth enhancement factor, β_{sp} ($=1 \times 10^{-5}$) is the spontaneous emission factor and ζ_m ($=50 \text{ cm}^{-1}$) is the total cavity loss. g_m is the optical gain, $g_{th,m}$ is the

Chapter 4 Study of ARROW VCSELs under External Optical Feedback

threshold gain [2] and α_m is the radiation loss. The optical feedback of photon density, $\text{Ref}_{S,m}$ and phase, $\text{Ref}_{\phi,m}$, can be written as

$$\text{Ref}_{S,m}(t) = k_{\text{ext}} \tau_L^{-1} \sqrt{S_m(t) S_m(t - \tau_{\text{ext}})} \cos(\theta_m(t)), \quad (4.3)$$

$$\text{Ref}_{\phi,m}(t) = -k_{\text{ext}} \tau_L^{-1} \sqrt{S_m(t - \tau_{\text{ext}}) / S_m(t)} \sin(\theta_m(t)), \quad (4.4)$$

where $\theta_m(t) = \phi_m(t) - \phi_m(t - \tau_{\text{ext}}) + \omega_{\text{th}} \tau_{\text{ext}}$, ω_{th} is the oscillation frequency at threshold, τ_{ext} is the external round trip delay time and τ_L ($= 0.15$ ps) is the round-trip time inside the laser cavity. It is noted that the optical feedback will not result in a significant change in temperature profile as it is mainly dependent on the distribution of injection current. Therefore, the variation of temperature is ignored in the above model in order to facilitate the study.

The feedback parameter, k_{ext} , is defined as $k_{\text{ext}} = \eta(1 - R_1) \sqrt{R_{\text{ext}}} / \sqrt{R_1}$, where R_{ext} is the external reflectivity, R_1 ($= 0.997$) is the reflectivity of DBRs and η ($= 0.4$) is the coupling between the external mirror and laser. If R_{ext} is set to 0.1, the corresponding value of k_{ext} is about 3.8×10^{-4} . It is noted that short-distance reflection has less influence on the transient response of VCSELs [3]. Hence, only long-distance reflection ($\tau_{\text{ext}} = 0.23$ ns) is considered in our analysis.

The rate equation of the carrier concentration used in this investigation is introduced in the preceding chapter, which is (3.8). A transparent electrode, which is used to inject current into the active layer, has a diameter of d_1 and is located on top of the p-DBR. The injection current density is described by equation (3.9), with r_o set to $1.5 \mu\text{m}$ to estimate the diffusion of injection current inside the p-DBR. The photon density and carrier concentration of the

Figure 4.2 Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, and $d_2 = 6 \mu\text{m}$ when injection current density is (a) 6.5 kA/cm², (b) 7 kA/cm², and (c) 8.5 kA/cm². ■ - LM₀₁ and ● - LM₁₁. The inserts give the transient response of LM₀₁ (solid line) and LM₁₁ (dashed line) over a time period of 2 ns.

ARROW VCSEL under the influence of external optical feedback are solved self-consistently.

The influence of radiation loss on the sensitivity of VCSELs to the optical feedback can be explained by the critical feedback strength, k_{crit} , which is defined as the minimum reflectivity to force the laser into coherence collapse regime. k_{crit} can be expressed as $k_{crit} = \tau_L \sqrt{2} \omega_r / \sqrt{1 + \alpha_H}$ where $\omega_r = \nu_g (\alpha_m + \zeta_m) S_m \partial g_m / \partial N$ is the relaxation oscillation frequency and $\partial g_m / \partial N$ is the differential gain coefficient [4]. This implies that under the influence of

external optical feedback, stable transient response of ARROW VCSELs can be enhanced if the value of α_m is increased through the increase of ω_r .

Two possible designs of ARROWs have been proposed to improve the performance of VCSELs: ARROWs are optimized for 1) minimum threshold current in [5, 6], and 2) maximum radiation loss margin (i.e., radiation loss difference between LM_{01} and LM_{11}) of VCSELs, which is described in the preceding chapter. The former (latter) approach will minimize (increase) the radiation loss of LM_{01} . Under the influence of external optical feedback, it is foreseen that the transient response of the two designs will exhibit differently due to the difference in radiation loss margin and k_{crit} (i.e., radiation loss of LM_{01}).

This can be demonstrated by first studying a 12- μm -core-diameter VCSEL with the design of ARROW for minimum threshold current. The corresponding values of s and d_2 are selected to be 2.4 μm and 6 μm , respectively, and the radiation loss of LM_{01} is minimized to $\alpha_1 = 0.5 \text{ cm}^{-1}$. The bifurcation diagrams are given in Figure 4.2 for the laser with an injection current of (a) 6.5kA/cm² (only LM_{01} is excited), (b) 7kA/cm² (threshold of LM_{11}), and (c) 8.5kA/cm² (both LM_{01} and LM_{11} are excited). In case (a), it is observed that LM_{11} is completely suppressed due to the design of ARROW. However, due to low output power and a small value of α_1 , the resulting value of k_{crit} is small, such that LM_{01} exhibits period-doubling route to chaos. In case (b), the increase in output power increases the value of k_{crit} resulting in the laser to be less sensitive to optical feedback. In case (c), further increase in injection current excites LM_{11} , due to spatial-hole-burning of the carrier concentration, which triggers

Figure 4.3 Radiation loss of the four lowest loss leaky modes plotted versus s with $d_2 = 3.9 \mu\text{m}$. Solid line – LM_{01} , dashed-dot line – LM_{11} , dashed line – LM_{02} , and dotted line – LM_{12} .

the unstable operation of VCSELs under external optical feedback. The bifurcation diagrams were plotted by random selection of peak-to-peak output power at some sampling time versus feedback parameter (k_{ext}). We increase the value of k_{ext} from 0 to a large enough value in order to observe the trend of chaos oscillation.

Figure 4.3 plots the radiation losses versus s for the four lowest transverse leaky modes (i.e., LM_{01} , LM_{11} , LM_{02} and LM_{12}) of ARROW with configuration of $d_1 = 12 \mu\text{m}$ and $d_2 = 3.9 \mu\text{m}$. The circle shows the choice of $s = 2.46 \mu\text{m}$ for the design of maximum radiation loss margin but the corresponding radiation loss of LM_{01} has increased to $\alpha_1 = 1.1 \text{ cm}^{-1}$.

Figure 4.4 Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, and $d_2 = 3.9 \mu\text{m}$ when injection current density is (a) 5.82 kA/cm^2 , (b) 6.42 kA/cm^2 , and (c) 7.22 kA/cm^2 . ■ - LM_{01} and ● - LM_{11} .

The corresponding bifurcation diagrams for the ARROW VCSELs are given in Figure 4.4. Three bias current densities are chosen so that the corresponding total output intensities (with $k_{\text{ext}} = 0$) of the VCSELs are about the same as that given in Figure 4.2. It is observed that LM_{11} is completely suppressed in the entire range of injection current due to the large radiation loss margin. Furthermore, LM_{01} exhibits lesser sensitivity to optical feedback than that of Figure 4.2. These observations are expected because 1) large radiation loss margin suppresses the excitation of LM_{11} at high bias and 2) large value of α_1 minimizes the sensitivity of LM_{01} to optical feedback at low bias. As a result, the influence of external optical feedback leading to higher order bifurcations and chaos is minimized.

Figure 4.5 Plot of maximum k_{ext} versus total output power for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, $d_2 = 6 \mu\text{m}$ (‘■’- minimum threshold current) and that with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, $d_2 = 3.9 \mu\text{m}$ (‘●’- maximum radiation loss margin).

Figure 4.5 delineates the sensitivity of LM_{01} to optical feedback for the two ARROW designs. The vertical axis of Figure 4.5 records the maximum value of k_{ext} at which stable single-mode operation can still be maintained. It is shown that the design of ARROW VCSELs with maximum radiation loss margin has stable high-power single-mode operation even under strong optical feedback.

The increase in threshold current density, J_{th} , due to the increase of α_m , can be estimated $J_{\text{th}} \approx J_o \exp((\alpha_m + \zeta_m)/\Gamma_z a_N)$, where J_o is a proportional constant and $a_N (=1.5 \times 10^3 \text{cm}^{-1})$ is the gain coefficient. Hence, if α_m increases from 0.5

cm^{-1} to 1.1 cm^{-1} , J_{th} will only increase by 1%. In fact, our numerical calculation has verified that the increase in J_{th} will not be more than 5%. The differential quantum efficiency, η_d , can be approximated by $\eta_d \approx \alpha_m / (\alpha_m + \xi_m)$. Hence, the reduction of η_d will be less than 3% if α_m increases from 0.5 cm^{-1} to 1.1 cm^{-1} . The fabrication tolerance is also studied. It can be shown that the insensitivity to external optical feedback can be maintained if the uncertainty of s and d_2 is less than $\pm 0.15 \text{ }\mu\text{m}$ and $\pm 0.25 \text{ }\mu\text{m}$, respectively from the optimum position. In addition, the variation of $\Delta n (= n_2 - n_1)$ should be less than 5%.

4.3 Conclusion

In conclusion, the capability of using ARROWs to suppress higher order bifurcations and chaos in VCSELs is studied. It is found that the design of ARROW with maximum radiation loss margin can stabilize high-power single-mode operation of VCSELs under the influence of strong external optical feedback. This is because large radiation loss margin suppresses the excitation of LM_{11} at high output powers such that the influence of LM_{11} on the stability of LM_{01} is minimized. In addition, the increase in radiation loss of LM_{01} (i.e., increase in k_{crit}) reduces the sensitivity to optical feedback thereby delaying the onset of chaos.

REFERENCES

- [1] C. W. Tee and S. F. Yu, "Design and analysis of cylindrical antiresonant reflecting optical waveguide," *Journal of Lightwave Technology*, vol. 21, pp. 3379-3386, Dec 2003.
- [2] S. F. Yu, "Nonlinear dynamics of vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 35, pp. 332-341, Mar 1999.
- [3] J. Y. Law and G. P. Agrawal, "Effects of optical feedback on static and dynamic characteristics of vertical-cavity surface-emitting lasers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 353-358, Apr 1997.
- [4] L. N. Langley and K. A. Shore, "Effect of optical feedback on the noise properties of vertical cavity surface emitting lasers," *IEE Proceedings-Optoelectronics*, vol. 144, pp. 34-38, Feb 1997.
- [5] T. W. Lee, S. C. Hagness, D. L. Zhou, and L. J. Mawst, "Modal characteristics of ARROW-type vertical-cavity surface-emitting lasers," *IEEE Photonics Technology Letters*, vol. 13, pp. 770-772, Aug 2001.
- [6] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.

CHAPTER 5

Suppression of Polarization Switching in Birefringent ARROW VCSELs

In this chapter, influence of birefringence on the multimode operation of ARROW VCSELs is analyzed. It can be shown that polarization switching is mainly due to thermal lensing effects. Hence, a new design rule is proposed to optimize the dimensions of ARROW for the suppression of polarization switching. Using the optimized design, the maximum single-polarization output power of VCSELs can be tripled. In addition, it is shown that the performance of the optimized ARROW VCSELs will not be deteriorated by the uncertainty of birefringence.

5.1 Introduction

In the preceding chapters, we have studied the multi-transverse leaky mode stability (i.e. the stability of single transverse mode output) of ARROW VCSELs, as well as ARROW VCSELs' single transverse mode output stability under external optical feedback. It should be noted that in the high-power operation of large-area VCSELs, another factor that may impair the overall output stability is the polarization switching, which is originated from the unintentional anisotropy of the semiconductor material induced from device fabrication.

In cylindrical VCSELs, because the waveguide is cylindrically symmetric, there exists a twofold degeneracy of the orthogonal polarizations for each transverse mode. The two orthogonal polarizations can be located at any azimuthal direction if the refractive index is uniform in all azimuthal directions. In this case, the transverse optical field profiles of the two polarizations are identical, so the two polarizations have same modal gain and thus can be excited simultaneously. However, when the unintentional anisotropy is introduced during the fabrication of VCSELs, the optical fields are no longer polarized arbitrarily, but polarized relative to a particular crystallographic plane. This is because the distribution of in-plane gain is dependent on the orientation of the crystallographic plane of the QW materials. It has been shown in many studies that the refractive index anisotropies can suppress one of the two orthogonal polarizations in the cylindrical VCSELs, especially with a large diameter [2],[4]. Therefore, it is believed anisotropy or birefringence may result in significant polarization instability.

It is found in large aperture ARROW VCSELs, birefringence can arise from the less controllable anisotropic strain/stress inside the dielectric multilayered structure [1]. In addition, the spatial-hole-burning (SHB) and thermal lensing effects [2] may alter the profiles of the two orthogonal polarizations. This is because the optical gain of the two orthogonal polarizations is also dependent on their transverse optical profiles, hence, the polarization switching is possible. Therefore, it is necessary to optimize the ARROW structure in order to sustain high-power single-polarization operation. However, a detailed analysis on the

Figure 5.1 Schematic of the birefringent ARROW VCSEL used in the analysis

above-threshold polarization characteristics of ARROW VCSELs is lacking. In addition, the capability of using ARROW to suppress polarization switching has not been explored. In this chapter, the polarization characteristics of ARROW VCSELs are studied. A new design-rule is also proposed to design ARROW VCSELs for high-power single-polarization operation. Furthermore, it can be shown that the performance of the optimized ARROW VCSEL is robust to the uncertainty of birefringence.

5.2 Model

Figure 5.1 shows the schematic of an ARROW VCSEL used in our analysis. The low index core region (with diameter $d_1 = 12 \mu\text{m}$) is surrounded by two

Chapter 5 Suppression of Polarization Switching in Birefringent ARROW VCSELs

reflectors, which are the 1st and 2nd cladding layers, with thickness of s and d_2 , respectively. In the absence of birefringence, the refractive indices of core, 1st, 2nd and the outer cladding layers are equal to $n_1 = 3.3$, $n_2 = 3.35$, $n_3 = 3.3$ and $n_4 = 3.35$, respectively. The polarization properties of cylindrical ARROW VCSELs are analyzed by studying the modal gain and radiation losses of the polarized transverse modes. In this investigation, only two transverse leaky modes (i.e., LM₀₁ and LM₁₁) with the lowest radiation losses are considered in our studies. This is because the other transverse leaky modes have radiation losses of at least 5cm⁻¹ higher than that of LM₁₁ in the ARROW structures under investigation. Furthermore, each transverse leaky mode has two orthogonal polarizations (i.e. v and h modes) inside the core region. Therefore, we will consider four polarized transverse leaky modes (i.e., LM₀₁ ^{h} , LM₀₁ ^{v} , LM₁₁ ^{h} & LM₁₁ ^{v}). The field intensity ψ_{m1}^i ($i = h, v$ and $m = 0, 1$) can be calculated by (3.3) respectively. In this study, the two effective modes for LM₁₁ corresponding to the sine and cosine azimuthal dependence (i.e. LM₁₁ ^{c} and LM₁₁ ^{s}) are totally identical and considered together as one transverse mode LM₁₁, to simplify the calculation. Therefore, the photon rate equations can be written as

$$\frac{dS_{m1}^v}{dt} = \nu_g \left(\Gamma_z \langle g_{m1}^v \rangle - \alpha_{m1}^v - \zeta_{m1}^v \right) S_{m1}^v + \beta_{sp} \Gamma_z B_{sp} \langle N_v \rangle^2, \quad (5.1)$$

$$\frac{dS_{m1}^h}{dt} = \nu_g \left(\Gamma_z \langle g_{m1}^h \rangle - \alpha_{m1}^h - \zeta_{m1}^h \right) S_{m1}^h + \beta_{sp} \Gamma_z B_{sp} \langle N_h \rangle^2, \quad (5.2)$$

where the subscripts v and h represents the two orthogonal polarizations. $S_{m1}^{v(h)}$

is the photon density of LM₁₁ ^{$v(h)$} . The modal gain, $\langle g_{m1}^\eta \rangle$, is given by

$$\langle g_{m1}^\eta \rangle = \frac{\int_0^{2\pi} \int_0^\infty g(N) |\psi_{m1}^\eta(r, \phi, t)|^2 r dr d\phi}{\int_0^{2\pi} \int_0^\infty |\psi_{m1}^\eta(r, \phi, t)|^2 r dr d\phi}, \quad (5.3)$$

where the optical gain of the QWs materials, $g(N)$, can be written as

$$g(N) = a_N \cdot \ln\left(\frac{N}{N_t}\right) \quad (5.4)$$

The definitions for other variables can be found in Chapter 3. The rate equation of carrier concentration can be expressed as

$$\begin{aligned} \frac{\partial N(r, t)}{\partial t} = D \left[\frac{1}{r} \frac{\partial N}{\partial r} + \frac{\partial^2 N}{\partial r^2} \right] - \frac{N}{\tau_N} + \frac{J(r, t)}{ed_a} \\ - g(N) \sum_{\eta=v, h} \left(a_{01}^\eta |\psi_{01}^\eta(r, t)|^2 S_{01}^\eta + a_{11}^\eta |\psi_{11}^\eta(r, t)|^2 S_{11}^\eta \right), \end{aligned} \quad (5.5)$$

where N is the carrier concentration, $a_{m1}^\eta = \pi v_g \Gamma R^2 / \int_0^{2\pi} \int_0^\infty |\psi_{m1}^\eta(r, \phi, t)|^2 r dr d\phi$ is

the normalizing constant. The definitions for other symbols can be found in Chapter 3. The models used to calculate the influences of SHB and heat have also been introduced in Chapter 3.

5.3 Numerical Simulations

With the model introduced above, four polarized transverse leaky modes (i.e., LM_{01}^h , LM_{01}^v , LM_{11}^h & LM_{11}^v), carrier concentration and heat now can be calculated self-consistently. In addition, the influence of SHB and thermal lensing effects (including carrier- and heat-induced index change) are carefully taken into consideration along the transverse and azimuthal directions. If the influence of birefringence is taken into consideration, the leaky modes LM_{01}^v &

Chapter 5 Suppression of Polarization Switching in Birefringent ARROW VCSELs

LM_{11}^v (LM_{01}^h & LM_{11}^h) will experience a small change in refractive index, Δn_v (Δn_h), inside the core region of the ARROW. The details of the parameters can be found in Table 5.1. These parameters are selected to be comparable with the ARROW VCSELs reported in [3] to make the simulation realistic.

Table 5.1

Device and Material Parameters

Symbol	Value	Meaning of the Symbol
λ	0.98 μm	free space wavelength
v_g	$83.3 \times 10^8 \text{ cm/s}$	group velocity
B_{sp}	$1 \times 10^{-10} \text{ cm}^3/\text{s}$	bimolecular recombination coefficient
β_{sp}	1×10^{-5}	spontaneous emission factor
N_t	$1.5 \times 10^{18} \text{ cm}^{-3}$	transparent carrier density
a_N	$1.5 \times 10^3 \text{ cm}^{-1}$	gain coefficient
$\zeta_{01}^{v,h}$	55 cm^{-1}	total cavity loss of LM_{01}
$\zeta_{11}^{v,h}$	60 cm^{-1}	total cavity loss of LM_{11}
D	1 cm^2/s	diffusion coefficient
Q	$1.602 \times 10^{-19} \text{ C}$	electron charge
d	$0.1 \times 10^{-4} \text{ cm}$	thickness of active layer
τ_N	1 ns	carrier lifetime
r_o	1.5 μm	effective diffusion length of the injection current
$\partial n / \partial T$	$\sim 3 \times 10^{-4} \text{ K}^{-1}$	heat induced index change coefficient

The influence of birefringence on the excitation of multi-transverse leaky modes in a 12- μm -core-diameter ARROW VCSEL is studied. It is assumed that the thickness of the cladding layers, s and d_2 , are set to 1.3 μm and 6 μm , respectively. These values of s and d_2 are selected under the planar approximation method for the minimum radiation loss of the fundamental transverse leaky mode [3].

Figure 5.2 shows the light-current curves and net optical gain versus injection current of the birefringent ARROW VCSELs. In the calculation, it is assumed

Figure 5.2 (a) Light-current curves and (b) net gain versus normalized injection current for the birefringent ARROW VCSELs with $s = 1.3 \mu\text{m}$, $d_2 = 6 \mu\text{m}$, $\Delta n_c = 2 \times 10^{-4}$, and $\Delta n_s = 0$ (reference point) for the four transverse leaky modes.

that $\Delta n_v = 2 \times 10^{-4}$ and $\Delta n_h = 0$ so that the resonant frequency of LM_{01}^v (LM_{11}^v) is slightly higher than that of LM_{01}^h (LM_{11}^h). The existence of Δn_v is due to strain-induced birefringence and its value is estimated from the wavelength difference (i.e., $\sim 0.5 \text{ \AA}$) between the two polarizations obtained experimentally [2]. In the calculation of Figure 5.2, the influence of birefringence and thermal effects was considered by including the refractive index change, which induced by both

birefringence and thermal effects, into the calculation of optical field profiles (Equation 3.4). The modal gain is dependent on the optical field (Equation 5.3), so it will eventually affect the photon population rate (Equation 5.1 and 5.2) and make the calculation of power and net gain possible.

It is observed that polarization switching between LM_{01}^v and LM_{01}^h occurs at injection level equal to $\sim 1.55 \times \text{threshold}$. The increase in (reduction of) modal gain (radiation loss), which is a function of the index profile, causes the polarization switching. It can be shown that the heat-induced index change can be $> 1 \times 10^{-2}$ (i.e. $\sim 1.2 \times 10^{-2}$), which is ~ 5 times greater than that can be obtained from the carrier-induced index change (i.e. $\sim 4 \times 10^{-3}$) [4]. Similar results can be found in Figure 9 of reference [4]. The simulation of the work shows that temperature-induced index change inside the laser cavity is the dominant mechanism of the polarization switching. Furthermore, the excitation and polarization switching of LM_{11}^v and LM_{11}^h , which are also dominated by thermal lensing effects, occur at injection level $\geq 2.1 \times \text{threshold}$.

Poor suppression of polarization switching in the birefringent ARROW VCSELs is mainly due to the small radiation loss difference between the LM_{01}^v and LM_{01}^h . Hence, a new design-rule, which 1) maximizes the radiation loss difference between LM_{01}^v and LM_{01}^h and 2) maintains a low radiation loss in LM_{01}^v , is proposed to optimize the ARROW structure for the suppression of polarization switching.

The design-rule can be implemented by the following steps: 1) Initially, the influence of birefringence is ignored (i.e., $\Delta n_v = \Delta n_h = 0$) in the design based on

Chapter 5 Suppression of Polarization Switching in Birefringent ARROW VCSELs

cold cavity analysis. For a given value of d_1 , the values of s and d_2 are optimized to minimize the radiation loss of LM_{01} . 2) Then, with the inclusion of birefringence into the cold cavity analysis (i.e., $\Delta n_v = 2 \times 10^{-4}$ & $\Delta n_h = 0$), the value of s is allowed to increase in order to increase the radiation loss difference between LM_{01}^v and LM_{01}^h . However, the variation of s is restricted to 1) the radiation loss of LM_{01}^v is not excessively higher than its minimum value, and 2) the radiation loss of LM_{11} (also other high-order transverse leaky modes) should be higher than that of LM_{01} . The value of d_2 is kept unchanged because the radiation loss difference is less dependent on d_2 .

The new design-rule is applied to design a 12- μm -core-diameter birefringent ARROW VCSEL: 1) The values of s and d_2 are calculated for minimum radiation loss of LM_{01} (for the case where $\Delta n_v = \Delta n_h = 0$). Figure 5.3a plots the radiation loss of LM_{01} versus s (i.e., $1 \mu\text{m} < s < 3 \mu\text{m}$) and d_2 (i.e., $3 \mu\text{m} < d_2 < 6 \mu\text{m}$) by cold-cavity simulation [5]. If $s < 2 \mu\text{m}$ is required in the design of ARROW, it can be shown that the optimum values of s and d_2 are found to be $1.3 \mu\text{m}$ and $3.93 \mu\text{m}$, respectively, with the corresponding radiation loss equal to $\sim 0.08 \text{ cm}^{-1}$. 2) Birefringence is now taken into consideration and the value of s is allowed to increase for a larger radiation loss difference between LM_{01}^v and LM_{01}^h . Figure 5.3b. shows the radiation loss difference between LM_{01}^v and LM_{01}^h versus s . It is observed that if s increases from $1.3 \mu\text{m}$ to $1.68 \mu\text{m}$, the corresponding radiation loss difference increases from $\sim 0.02 \text{ cm}^{-1}$ to $\sim 6 \text{ cm}^{-1}$, respectively. The solid, dashed, dotted and dashed-dotted lines in the figure represent $\Delta n_c = 2 \times 10^{-4}$, 5×10^{-4} , 8×10^{-4} and 10×10^{-4} , respectively, but the other parameters remain unchanged. This indicated that the variation of Δn_v will not

deteriorate the radiation loss difference between LM_{01}^v and LM_{01}^h at $s = \sim 1.68$ μm , and the suppression of polarization switching is therefore robust to the uncertainty of Δn_c . Radiation losses of all transverse leaky modes are also calculated for $s = 1.68$ μm and $d_2 = 3.93$ μm . It can be shown that LM_{01}^v has the

Figure 5.3 (a) Plots of radiation loss of LM_{01} versus s and d_2 . The inserted diagram is the enlargement of radiation loss of LM_{01} in range of $1 \mu\text{m} < s < 1.5 \mu\text{m}$ and $2 \mu\text{m} < d_2 < 6 \mu\text{m}$. **(b)** Radiation loss difference between LM_{01}^v and LM_{01}^h for Δn_v varies between 2×10^{-4} and 1×10^{-3} .

lowest radiation loss and the mode with the second lowest loss is LM_{01}^h , followed by LM_{11}^v and LM_{11}^h . Other high order transverse leaky modes have much higher radiation losses so can be ignored in the analysis.

Figure 5.4 shows the steady-state characteristics of the ARROW VCSELs with dimensions obtained by the new design-rule (i.e., $s=1.68\ \mu\text{m}$, $d_2=3.93\ \mu\text{m}$). From the light-current curves, it is found that the maximum power of LM_{01}^v

Figure 5.4 (a) Light-current curves and (b) net gain versus normalized injection current for the new designed birefringent ARROW VCSELs with $s = 1.68\ \mu\text{m}$, $d_2 = 3.93\ \mu\text{m}$, $\Delta n_v = 2 \times 10^{-4}$, and $\Delta n_h = 0$ for the four polarized transverse leaky modes.

increases from ~ 3 mW to ~ 10.8 mW (i.e., improved by more than 3 times). In addition, the required injection current to switch from LM_{01}^v to LM_{01}^h increases from $1.57 \times \text{threshold}$ to $2.1 \times \text{threshold}$. It can also be shown that the threshold current for the optimized structure is only slightly increased by less than 10%. Hence, it is possible to suppress polarization switching in VCSELs using optimized ARROW structure.

5.4 Discussion and Conclusion

In conclusion, the above-threshold characteristics of birefringent ARROW VCSELs are studied in this chapter. It can be shown that polarization switching and excitation of high-order transverse leaky modes are mainly affected by thermal lensing effects. A new design-rule is also proposed to optimize the dimensions of ARROW VCSELs for better suppression of polarization switching. Hence, it can be shown that the maximum single-polarization output power can be improved by more than 3 times. Furthermore, the performance of the optimized ARROW VCSELs will not be deteriorated by the uncertainty of birefringence.

REFERENCES

- [1] M. P. vanExter, A. K. J. vanDoorn, and J. P. Woerdman, "Electro-optic effect and birefringence in semiconductor vertical-cavity lasers," *Physical Review A*, vol. 56, pp. 845-853, Jul 1997.
- [2] Y. Hong, K. A. Shore, A. Larsson, M. Ghisoni, and J. Halonen, "Polarisation switching in a vertical cavity surface emitting semiconductor laser by frequency detuning," *IEE Proceedings-Optoelectronics*, vol. 148, pp. 31-34, Feb 2001.
- [3] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.
- [4] S. F. Yu, "Polarization selection in birefringent antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 39, pp. 1362-1371, Nov 2003.
- [5] C. W. Tee, C. C. Tan, and S. F. Yu, "Design of antiresonant-reflecting optical waveguide-type vertical-cavity surface-emitting lasers using transfer matrix method," *IEEE Photonics Technology Letters*, vol. 15, pp. 1231-1233, Sep 2003.

CHAPTER 6

Analysis and Design of Large-area Anti-Resonant Reflecting Optical Waveguide Vertical-Cavity Semiconductor Optical Amplifiers

In the preceding chapters, large-area anti-resonant reflecting optical waveguide (ARROW) vertical-cavity surface-emitting lasers (VCSELs) are studied and optimized to achieve stable high-power single-mode operation. On the other hand, it is expected that the optical characteristics of ARROW vertical-cavity semiconductor-optical-amplifiers (VCSOAs) can be similar to that of the ARROW VCSELs. Hence, we extended our previous research knowledge of ARROW VCSELs to investigate the optical characteristics of ARROW VCSOAs in this chapter. Influence of spatial-hole-burning and thermal lensing on the stability of the amplified output signal is taken into consideration in the studies. A design rule, which can be used to deduce the optimized dimensions of ARROW, is developed to achieve spatially stable single-spot amplified output-signal in large-area VCSOAs. It can be shown that high saturation power, yet stable output signal can be achieved in large-area ARROW VCSOAs simultaneously.

6.1 Introduction

VCSOAs are a cost-effective alternative to the conventional in-plane edge-emitting semiconductor optical amplifiers due to their compactness in size, high

coupling efficiency to optical fiber, insensitivity to polarization, low noise figure, and the possibility to fabricate on-wafer high-density optical amplifier arrays. Recently, index-guided VCISOAs with core diameter of 9 μm have been demonstrated to achieve reflection gain of ~ 24 dB [1]. Large-area VCISOAs with core diameter of 50 μm have also been fabricated to improve saturation power. High saturation power of large-area VCISOAs can be achieved but at the sacrifice of stable spatially amplified output signal [2]. It is believed that the unstable output behavior of VCISOAs is triggered by spatial-hole-burning (SHB) and thermal lensing, which are usually ignored in the study of VCISOAs. Hence, in order to achieve stable amplified output signal in large-area VCISOAs, the excitation of higher-order transverse cavity modes has to be suppressed during the amplification process.

In this chapter, it is proposed that using anti-resonant reflecting optical waveguide (ARROW) in large-area VCISOAs to sustain stable amplification of fundamental transverse cavity mode. This is possible because it has been shown higher-order transverse cavity modes in large-area VCSELs can be suppressed effectively by ARROW. Hence, it is expected that ARROW will also favor to maintain stable single-spot amplified output signal in large-area VCISOAs. Therefore in this chapter, a self-consistent model, with the effects of SHB and thermal lensing, is developed to analyze the amplifier gain of ARROW VCISOAs. After that, the optical characteristics of ARROW VCISOAs under the influence of SHB and thermal lensing are studied and compared with that of the conventional index-guided VCISOAs. In addition, a new design rule, which can be used to deduce the optimized dimensions of ARROW, is proposed to achieve spatially stable single-spot amplified spot output signal in large-area VCISOAs.

It is then shown that high saturation power and stable amplified output signal can be obtained simultaneously in large-area ARROW VCSOAs by the new design rule.

6.2 Theoretical Model

Figure 6.1 shows the schematic of a 1.3- μm ARROW VCSOA. It is assumed that the VCSOA is electrically pumped by a transparent circular metal-contact covering the core region of the laser. The active layer, which consists of compressively strained InGaAsP/InP quantum wells (QWs), has peak optical gain at $\sim 1.32 \mu\text{m}$ under room temperature conditions. The typical reflectivity of the top (bottom) DBR, R_t (R_b), is assumed to be 0.918 (0.999). The ARROW

Figure 6.1 Schematic of an ARROW VCSOA operating in reflection mode.

structure is realized by etching the thin spacer layer of the VCSOA selectively [3]. Low index core region of the ARROW with diameter of d_1 is surrounded by two reflectors, which are the 1st and 2nd cladding layers with thickness of s and d_2 , respectively. The effective refractive indices of core, 1st, 2nd and the outer cladding layers are assumed to be $n_1 = 3.3$, $n_2 = 3.35$, $n_3 = 3.3$ and $n_4 = 3.35$, respectively. These values of refractive indices are typical values for the study of cylindrical ARROW devices [3].

The most important feature of ARROW is that the higher order transverse cavity modes will suffer larger radiation loss than that of the fundamental transverse mode. In our previous studies of ARROW VCSELs, it is found only the two lowest order transverse modes (i.e. LM_{01} and LM_{11}) can survive and all other modes are completely suppressed due to their large radiation losses. The situation will be the same in ARROW VCSOAs due to the similar waveguide characteristics. Therefore in this investigation, it is assumed that the ARROW VCSOA can only support amplified output signal with two spatial profiles (i.e., two transverse leaky modes – LM_{01} and LM_{11} , where LM stands for leaky modes. The transverse field profile ψ_{m1}^i and transverse propagation coefficient β_{m1}^i of LM_{01} and LM_{11} inside the ARROW VCSOA can be calculated from the scalar Helmholtz equation [4]

$$\left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + n_0^2 k_0^2 - (\beta_{m1}^i)^2 \right) \psi_{m1}^i = 0, \quad (6.1)$$

where r and ϕ are the transverse and azimuthal directions, respectively. $i = c$ or s , m ($= 0, 1$) is an integer represents the order of modes (for $m = 0$, the LM_{01} mode is independent on azimuthal direction so that the superscript c or s is

ignored), n_0 is the refractive index profile of the ARROW, $k_0 (= 2\pi/\lambda_0)$ is the wave vector and λ_0 is the operating wavelength. As introduced in the Chapter 3, the solutions to (6.1) can be expressed as

$$\begin{aligned}\psi_{m1}^c &= [E^+ H_v^{(1)}(\beta_{m1}^c r) + E^- H_v^{(2)}(\beta_{m1}^c r)] \cos(m\phi) \\ \psi_{m1}^s &= [E^+ H_v^{(1)}(\beta_{m1}^s r) + E^- H_v^{(2)}(\beta_{m1}^s r)] \sin(m\phi),\end{aligned}\quad (6.2)$$

where E^+ (E^-) is the positive (negative) traveling field amplitude along the transverse direction, and $H_v^{(1)}$ ($H_v^{(2)}$) is the v^{th} -order Hankel function of the 1st (2nd) kind.

The amplified signal obtained from a VCSOA can be detected from two directions: the transmission direction (i.e. same direction as the input signal) and the reflection direction (i.e. opposite direction of the input signal). The power ratio of the transmission (reflection) output signal over the input signal is defined as the transmission (reflection) gain. In addition the spontaneous emission inside the VCSOA cavity will also be amplified. The power ratio of its output amplified signal (ASE) over the original spontaneous emission signal is defined as the ASE gain. The transmission gain ($G_{t,m1}^i$), reflection gain ($G_{r,m1}^i$) and amplified spontaneous emission (ASE) gain ($G_{\text{ASE},m1}^i$) of the ARROW VCSOAs with the consideration of LM₀₁ and LM₁₁ can be written as [5]

$$G_{t,m1}^i = \frac{(1 - R_t)(1 - R_b) \langle g_{s,m1}^i \rangle}{\left(1 - \sqrt{R_t R_b} \langle g_{s,m1}^i \rangle\right)^2 + 4\sqrt{R_t R_b} \langle g_{s,m1}^i \rangle \sin^2 \phi_{m1}^i}, \quad (6.3)$$

$$G_{r,m1}^i = \frac{\left(\sqrt{R_t} - \sqrt{R_b} \langle g_{s,m1}^i \rangle\right)^2 + 4\sqrt{R_t R_b} \langle g_{s,m1}^i \rangle \sin^2 \theta_{m1}^i}{\left(1 - \sqrt{R_t R_b} \langle g_{s,m1}^i \rangle\right)^2 + 4\sqrt{R_t R_b} \langle g_{s,m1}^i \rangle \sin^2 \theta_{m1}^i}, \quad (6.4)$$

$$G_{\text{ASE},m1}^i = \frac{\sqrt{\langle g_{s,m1}^i \rangle} \sum_{(j1,j2)=(t,b)} (1-R_{j1}) \left(1 + \sqrt{R_{j2} \langle g_{s,m1}^i \rangle}\right)^2}{2 \left(1 + \sqrt{R_t \langle g_{s,m1}^i \rangle}\right) \left(1 + \sqrt{R_b \langle g_{s,m1}^i \rangle}\right) \left(1 - \sqrt{R_t R_b \langle g_{s,m1}^i \rangle}\right)}, \quad (6.5)$$

where θ_{m1}^i is the single-pass phase detuning, and $\langle g_{s,m1}^i \rangle$ is the spatial average single pass gain as defined by

$$\langle g_{s,m1}^i \rangle = \exp \left[(\Gamma \xi \langle g_{m1}^i \rangle - \alpha_{m1}^i - \zeta_{m1}^i) L_{\text{eff}} \right]. \quad (6.6)$$

The spatial-average modal gain, $\langle g_{m1}^i \rangle$, can be expressed as

$$\langle g_{m1}^i \rangle = \frac{\int_0^{2\pi} \int_0^\infty g |\psi_{m1}^i|^2 r dr d\phi}{\int_0^{2\pi} \int_0^\infty |\psi_{m1}^i|^2 r dr d\phi}, \quad (6.7)$$

where g is the material gain to be defined. In (6.7), we have implicitly taken into the consideration of the transverse confinement of the optical modes. ξ ($= 1.7$) is the longitudinal gain enhancement factor, L_{eff} ($= 2.2 \mu\text{m}$) is the effective cavity length [6] and, Γ ($= 0.056$) is the longitudinal confinement factor. α_{m1}^i ($= 2 \times \text{Im}(\beta_{m1}^i) / k_0$) is the radiation loss of the leaky modes and ζ_{m1}^i ($\zeta_{01} = 15 \text{ cm}^{-1}$, $\zeta_{11}^c = \zeta_{11}^s = 20 \text{ cm}^{-1}$) is the sum of all the other internal losses inside the cavity [6]. The VCSOAs under investigation are operated in reflection mode, therefore only the reflection gain of the optical amplifier is considered in the model.

The photon rate equations for ARROW VCSOA is given by

Chapter 6 Analysis and Design of Large-area ARROW VCISOAs

$$\frac{dS_{m1}^i}{dt} = v_g (\Gamma \xi \langle g_{m1}^i \rangle - \alpha_{m1}^i - \tilde{\alpha}_{m1}^i - \zeta_{m1}^i) S_{m1}^i + \frac{P_{I,m1}^i}{h \nu_0 V_p} + \gamma_{s,m1}^i \Gamma B_{sp} \langle N^2 \rangle, \quad (6.8)$$

where S_{m1}^i is the photon density of the m^{th} mode, h is the plank constant, v_g ($= 90.9 \times 10^8$ cm/s) is the group velocity, ν_0 ($= c_0/\lambda_0$) is the signal's frequency in vacuum, c_0 ($= 3 \times 10^{10}$ cm/s) is the velocity of light in free space, V_p ($= \pi R^2 L_{\text{eff}}$) is the effective volume occupied by the leaky modes, $R = d_1/2 + s + d_2$ and B_{sp} ($= 1 \times 10^{-10}$ cm³/s) is the bimolecular recombination coefficient. $\gamma_{s,m1}^i$ ($\gamma_{s,01}^i = 0.01$ and $\gamma_{s,11}^c = \gamma_{s,11}^s = 0.005$) describes the fraction of total spontaneous emission that radiates into the corresponding mode and $\langle N^2 \rangle$ has expression similar to that of $\langle g_{m1}^i \rangle$. $P_{I,m1}^i$ is defined as the photon power from the input signal coupled to LM_{m1}^i . In (6.8), the wavelength dependence of $\langle g_{m1}^i \rangle$ is ignored in the calculation as the material gain bandwidth (i.e., > 30 nm) is usually much wider than that of the operating signals (i.e., < 3 nm) inside the ARROW VCISOAs. In addition, it is assumed that $P_{I,11}^c = P_{I,11}^s$ and the input power ratio between LM_{01} and LM_{11} is 20dB (i.e., $P_{I,01}/(P_{I,11}^c + P_{I,11}^s) = 100$). This implies that the injected signal power is mainly coupled to LM_{01} , however, higher-order transverse cavity modes can still be excited by the nonlinear processes (i.e., SHB and thermal lensing). The symbol $\tilde{\alpha}_{m1}^i$ stands for the apparent mirror loss and is given by

$$\tilde{\alpha}_{m1}^i = \left(\Gamma \xi \langle g_{m1}^i \rangle - \alpha_{m1}^i - \zeta_{m1}^i \right) \frac{(G_{r,m1}^i + G_{t,m1}^i) P_{I,m1}^i + G_{ASE,m1}^i h \nu_0 \Gamma V_p \gamma_{s,m1}^i B_{sp} \langle N^2 \rangle}{(G_{r,m1}^i + G_{t,m1}^i - 1) P_{I,m1}^i + (G_{ASE,m1}^i - 1) h \nu_0 \Gamma V_p \gamma_{s,m1}^i B_{sp} \langle N^2 \rangle} \quad (6.9)$$

The rate equation of carrier concentration is same as the carrier rate equation for ARROW VCSELs and can be found in (3.10) ~ (3.15). In the study of ARROW VCISOAs, we assume the refractive index is independent on ϕ . Other factors that may cause a difference in LM_{11}^c and LM_{11}^s are: 1) the non-uniform azimuthal distribution of J ; 2) the difference in input signal power (i.e. azimuthal non-uniform input signal beam profile); 3) azimuthal non-uniform distribution of carrier concentration. For simplicity, it is assumed the input signal beam profile is azimuthal independent. However, neither the conditions 1), 2) nor 3) are be satisfied, so it is true that $\psi_{11}^c(r, \phi, t)$ and $\psi_{11}^s(r, \phi, t)$ only have the $\pi/2$ azimuthal profile difference (i.e., $\psi_{11}^c(r, t) = \psi_{11}^s(r, t) = \psi_{11}(r, t)$). As a result, $\alpha_{11}^c = \alpha_{11}^s$, $\langle g_{11}^c \rangle = \langle g_{11}^s \rangle$, $S_{11}^c = S_{11}^s$, and $N_{c2} = 0$ (i.e., $N(r, \phi, t) = N_{c0}(r, t)$). Hence, (3.23) for this study of ARROW VCISOAs can be simplified to

$$\frac{\partial N_{c0}(r, t)}{\partial t} = D \left[\frac{1}{r} \frac{\partial N_{c0}}{\partial r} + \frac{\partial^2 N_{c0}}{\partial r^2} \right] - \frac{N_{c0}}{\tau_N} + \frac{J(r, t)}{ed_a} - g(N) \left(a_{01} |\psi_{01}(r, t)|^2 S_{01} + \frac{1}{2} a_{11} |\psi_{11}(r, t)|^2 S_{11} \right) \quad (6.10)$$

where $S_{11} = S_{11}^c + S_{11}^s$, $a_{01} = \frac{1}{2} v_g \Gamma R^2 \int_0^\infty |\psi_{01}(r, t)|^2 r dr$ and

$a_{11} = v_g \Gamma R^2 \int_0^\infty |\psi_{11}(r, t)|^2 r dr d\phi$. The carrier-induced refractive index change,

δn_N , can be expressed as [7]

$$\delta n_N = -\alpha_H \frac{\lambda}{4\pi} \Gamma \frac{\partial g}{\partial N} \Delta N, \quad (6.11)$$

where $\alpha_H (= 3)$ is the linewidth enhancement factor, ΔN is the change of carrier concentration and $\partial g / \partial N$ is the differential gain. The influence of thermal

lensing can also be included into the model by solving the heat equation using Green's model [8]. The heat sources inside the VCSOAs aroused due to Joule heating. The heat density, Q_i , which is caused by the resistivity of all layers inside the VCSOAs, can be expressed as $Q_i = J^2 \rho_i$, where ρ_i is the resistivity of the i^{th} layer. The heat density of active layer, Q_a , contributed by non-radiative recombination and absorption of spontaneous emission, can be calculated by $Q_a = d_a^{-1} V_J (1 - \eta_{\text{sp}} f_{\text{sp}}) J (1 - \eta_i)$, where V_J is the junction voltage and, f_{sp} ($= 0.667$) is the fraction of spontaneous light which escaped from the cavity. η_{sp} ($= 0.5$) and η_i ($= 0.9$) are the internal quantum efficiencies for spontaneous and stimulated emission, respectively. In the calculation of Joule heating inside the ARROW VCSOAs, only the top p-DBR including the index spacer layer (with an effective resistivity of $\rho_p = 0.23 \text{ ohm}\cdot\text{cm}$), upper and lower confinement layer (with $\rho_n = 0.245 \text{ ohm}\cdot\text{cm}$), the bottom n-DBR (with $\rho_n = 3.19 \times 10^{-2} \text{ ohm}\cdot\text{cm}$) and the n-substrate (with $\rho_s = 4 \times 10^{-3} \text{ ohm}\cdot\text{cm}$) are taken into consideration. Please refer to Figure 6.1 for the location of the dielectric layers. Furthermore, the junction voltage $V_J(r)$ can be written as

$$V_J(r, t) = \frac{1}{\beta_J} \log \frac{J(r, t)}{J_s} \quad (6.12)$$

where J_s ($= 4 \times 10^{-9} \text{ A/cm}^2$) is the reverse saturation current density, $\beta_J = q/n_J K_b T$, K_b ($= 1.3807 \times 10^{-23} \text{ J/K}$) is the Boltzmann constant, T is the temperature and, n_J ($= 2.0$) is the ideality factor. The heat induced refractive index change, δn_T , can be expressed as follows

$$\delta n_T = \frac{\partial n}{\partial T} \Delta T, \quad (6.13)$$

where $\partial n/\partial T (\sim 3 \times 10^{-4} \text{ K}^{-1})$ is the heat induced index change coefficient and ΔT is the change of temperature from background. Hence, the influence of SHB and thermal lensing on the variation of ψ_{m1}^i and β_{m1}^i can be calculated by (6.1) with $n_0 = n_B + \delta n_N + \delta n_T$ where n_B is the background index profile of ARROW.

Optical gain of the QWs at signal wavelength $\sim 1.32 \text{ }\mu\text{m}$ can be approximated by [1]

$$g(N) = g_0 \log \left(\frac{N + N_s}{N_{tr} + N_s} \right), \quad (6.14)$$

where g_0 is the gain parameter, N_{tr} is the transparency carrier density, and N_s is a fitting parameter. Although these parameters are functions of temperature, the below-threshold operation of VCSOAs will only allow the variation of temperature to be no larger than 10K [9]. Hence, we ignored the heat dependence of g_0 , N_{tr} , and N_s in the calculation and their values are assumed to be equal to 1580 cm^{-1} , $1.1 \times 10^{18} \text{ cm}^{-3}$ and $-0.63 \times 10^{18} \text{ cm}^{-3}$ at room temperature, respectively. This approximation is valid because the stability of output amplified signal is mainly affected by the refractive index profile of the ARROW.

6.3 Simulation Results

In this section, the stability of amplified output signal of ARROW VCSOAs is analyzed by calculating the amplifier gain difference between LM₀₁ and LM₁₁. Firstly, the optical characteristics of ARROW and conventional index-guided VCSOAs are studied and compared. Then, the influence of SHB and thermal lensing on the amplifier gain of ARROW VCSOAs is investigated at various pumped and input signal powers. A new design rule to optimize the

Figure 6.2 Amplifier gain versus (a) input signal wavelength and, (b) pump current of an ARROW VCSOA with $d_1 = 12 \mu\text{m}$, $s = 2.89 \mu\text{m}$, $d_2 = 6 \mu\text{m}$. The arrows indicate the increase of pump current (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$). λ_{p01} and λ_{p11} are the resonant wavelength of LM_{01} and LM_{11} , respectively.

dimensions of large-area ARROW for maximum radiation loss margin is also developed. Hence, the possibilities to achieve stable single-spot amplified output signal from large-area ARROW VCSOAs are studied.

6.3.1. Stability of Amplified Output Signal – Comparison between ARROW and Conventional Index-guided VCSOAs

The differences in amplifier gain, $G_{r,m1}$, of ARROW and index-guided VCSOAs are analyzed and compared. In the study of ARROW VCSOAs, the values of d_1 , d_2 and s are optimized to 12, 6 and $2.98 \mu\text{m}$, respectively for a

Figure 6.3 Amplifier gain versus (a) input signal wavelength and, (b) pump current of a conventional index-guided VCSOA with $d_1 = 12\mu\text{m}$, $n_1 = 3.3$ and $n_2 = n_3 = n_4 = 3.25$. The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{th}$).

minimum radiation loss in LM_{01} (i.e., minimum threshold pump current, J_{th}). The radiation loss of LM_{01} (LM_{11}) is found to be 0.49cm^{-1} (3.23 cm^{-1}) and the corresponding value of J_{th} is obtained to be $\sim 4.95\text{ kA/cm}^2$.

Figure 6.2 plots the dependence of amplifier gain, $G_{r,m1}$, on signal wavelength, λ_0 , and pump current, J , of the ARROW VCSOA. For the index-guided VCSOA, it is assumed that $d_1 = 12\mu\text{m}$, $n_1 = 3.3$, and $n_2 = n_3 = n_4 = 3.25$ and the other parameters are identical to that of the ARROW VCSOA. These values of refractive indices ensure a resonant wavelength that matched with the ARROW VCSOA. J_{th} of the index-guided VCSOA is found to be ~ 4.79

kA/cm^2 . Figure 6.3 shows the dependence of $G_{r,m1}$ on λ_0 and J of the index-guided VCSOA.

From Figures 6.2a and 6.3a, it is observed that the peak gain value of LM_{01} , $G_{r,01}(\lambda_{p,01})$, for both ARROW and index-guided VCSOAs, remain unchanged over the range of J (i.e. 0.6, 0.8, $0.9.8 \times J_{\text{th}}$). $\lambda_{p,01}$ denotes the resonant wavelength of LM_{01} . The results delineate that the use of ARROW will not deteriorate the amplifier gain of VCSOAs. Furthermore, it is observed from Figures 6.2b and 6.3b that the peak gain of LM_{11} , $G_{r,11}(\lambda_{p,11})$, of the ARROW VCSOA is much lower than that of the index-guided VCSOA where $\lambda_{p,11}$ is the resonant wavelength of LM_{11} . At $J = 0.98 \times J_{\text{th}}$, the peak gain difference, $G_{r,01}(\lambda_{p,01}) - G_{r,11}(\lambda_{p,11})$, of ARROW VCSOA is greater than 16 dB. However, for the index-guided VCSOA, the peak gain difference is around 1.7 dB. Therefore, the amplification of LM_{11} is strongly suppressed in ARROW VCSOAs as compared to that of index-guided VCSOAs. This leads to a more stable single-spot amplified output signal emitted from the ARROW VCSOAs.

Figure 6.4 Transverse distributions of (a) carrier concentration, (b) carrier-induced index change, (c) temperature and heat-induced index change, (d) total index change and (e) field intensity of LM_{01} and LM_{11} versus pump current. The arrows indicate the increase of J (from 0.6, 0.8 to $0.98 \times J_{th}$). (f) Amplifier gain versus signal wavelength for $J = 0.6$ and $0.98 \times J_{th}$. The dashed lines indicate the calculation without the consideration of SHB and thermal lensing.

6.3.2 Influence of SHB and Thermal Lensing on the Stability of Amplified Output Signal of ARROW VCSOAs

The influence of SHB and thermal lensing on the optical characteristics of ARROW VCSOAs is studied. Figure 6.4 plots the optical characteristics of the 12- μm ARROW VCSOA for different value of J (from 0.6 to $0.98 \times J_{\text{th}}$) and with $P_{\text{I},01}$ set to a value of -50 dBm. Figure 6.4a shows the transverse distribution of carrier concentration, N , inside the active layer. As the injected photon density inside the VCSOA is relatively low (i.e., below saturation), the distribution of N is nearly uniform within the core region (i.e. $r \leq d_1$) for J up to $0.98 \times J_{\text{th}}$. Therefore, the influence of SHB is not significant for $J \leq 0.98 \times J_{\text{th}}$.

The corresponding change in refractive index, δn_{N} , is also given in Figure 6.4b. Figure 6.4c shows the transverse distribution of temperature, ΔT , and the heat-induced refractive change, δn_{T} , inside the active layer of the ARROW VCSOA. As ΔT and δn_{T} have a linear relationship according to (6.13), a set of curves is shown in Figure 6.4c to represent both parameters. Heat is generated inside the core region due to Joule heating as it is observed that the value of δn_{T} inside the core region is higher than that of the cladding region (i.e., $r > d_1$). The resultant change in refractive index, Δn , as shown in Figure 6.4d caused the spatial distribution of LM_{01} and LM_{11} , $|\psi_{\text{ml}}|^2$, to be focused into the core region at high values of J , as shown in Figure 6.4e. This is due to the dominant influence of thermal lensing over SHB under high values of J .

Figure 6.5 Amplifier gain versus signal wavelength for $J = 0.6$ and $0.98 \times J_{th}$ of index-guided VCSOAs with $d_1 = 12 \mu\text{m}$. The dashed lines indicate the calculation without the consideration of SHB and thermal lensing.

The amplifier gain spectra of both LM_{01} and LM_{11} , $G_{r,01}$ and $G_{r,11}$, are plotted in Figure 6.4f, for different value of J ($= 0.6$ and $0.98 \times J_{th}$). The solid (dashed) lines show the profile of the gain spectra with (without) the effects of SHB and thermal lensing. It is noted that the peak gain difference between LM_{01} and LM_{11} (i.e. $G_{r,01}(\lambda_{p,01}) - G_{r,11}(\lambda_{p,11})$) is 0.5 dB and 16 dB for $J = 0.6$ and $0.98 \times J_{th}$, respectively, when SHB and thermal lensing is considered. The red-shift of cavity resonance, $\lambda_{p,m1}$ ($\Delta\lambda_{p,01} \approx \Delta\lambda_{p,11} \approx 0.1 \text{ nm}$) at $J = 0.98 \times J_{th}$ verified the dominant effects of thermal lensing in VCSOAs. At $J = 0.6 \times J_{th}$, a blue-shift is observed due to the increase of N inside the core region.

For index-guided VCSOAs with $d_1 = 12 \mu\text{m}$, the dependence of Δn , ΔT , and δn_T on J is similar to that of ARROW VCSOAs so is not repeated. Figure 6.5 shows the corresponding amplifier gain spectra of both LM_{01} and LM_{11} , $G_{r,01}$ and $G_{r,11}$, with different value of J ($= 0.6$ and $0.98 \times J_{\text{th}}$). The peak gain difference between LM_{01} and LM_{11} (i.e. $G_{r,01}(\lambda_{p,01}) - G_{r,11}(\lambda_{p,11})$) is 0.16 dB and 1.4 dB for $J = 0.6$ and $0.98 \times J_{\text{th}}$, respectively, when SHB and thermal lensing is considered. It is noted that although the dependence of $G_{r,01}$ and $G_{r,11}$ on J for

Figure 6.6 Transverse distribution of (a) carrier concentration, (b) carrier-induced and heat-induced index changes, (c) total index change versus input signal power. (d) Amplifier gain of LM_{01} and LM_{11} versus input signal power. The arrows indicate the increase in $P_{I,01}$ (from -50 dBm to -10 dBm with 10 dBm interval).

the index-guided VCSOAs is similar to that of the ARROW VCSOAs, the corresponding peak gain difference is smaller.

The influence of SHB and thermal lensing on $G_{r,m1}$ of ARROW VCSOAs with the variation of $P_{I,01}$ is also studied. Figure 6.6 shows the optical characteristics of ARROW VCSOAs for values of $-50 \text{ dBm} \leq P_{I,01} \leq -10 \text{ dBm}$. The ARROW VCSOA is biased at $0.9 \times J_{th}$. As shown in Figure 6.6a, the effect of SHB is evident with increasing $P_{I,01}$. This is caused by the increase of the photon density of LM_{01} due to high amplifier gain of LM_{01} inside the cavity. On the other hand, heat generation inside the amplifier is mainly due to the Joule heating and has less dependence on the photon density. Therefore, the corresponding spatial distribution of ΔT and δn_T , as given in Figure 6.6b, are similar to the cases given in Figure 6.4c.

The resultant refractive index change, Δn , versus $P_{I,01}$ is depicted in Figure 6.6c. The increase in $P_{I,01}$ increases the value of Δn inside the core region. This sets up a “lens” in the core region and results $|\psi_{m1}|^2$ of LM_{01} to be focused into the centre of the core region. Figure 6.6d shows $G_{r,m1}$ versus $P_{I,01}$ biased at $J = 0.9 \times J_{th}$. It is observed that $G_{r,01}$ decreases faster than $G_{r,11}$ with the increase of $P_{I,10}$ because of the reduction in N inside the core region due to the effects of SHB. The saturation input power for LM_{01} is about -19 dBm . The influence of SHB is less evident in $G_{r,11}$ because the profile of $|\psi_{m1}|^2$ is located away from the “spatial hole” which is the centre of the core region.

Figure 6.7 plots the $G_{r,m1}$ of the index-guided VCSOA biased at $J = 0.9 \times J_{th}$ versus $P_{I,01}$. It is noted that the optical characteristics of the index-guided VCSOAs are similar to that of ARROW VCSOAs except the index-guided

VCSOAs have a smaller peak gain difference. The saturation input power for the LM_{01} is about -20 dBm. Hence, we have shown that the ARROW VCSOAs has better suppression to the amplification of LM_{11} as compared to that of the index-guided VCSOA even under the influence of SHB and thermal lensing effects.

Figure 6.7 Amplifier gain of LM_{01} and LM_{11} versus input signal power of index-guided VCSOAs with $d_1 = 12$ μm . The arrows indicate the increase in $P_{1,01}$ (from -50 dBm to -10 dBm with 10 dBm interval).

6.3.3. Design and Optimization of Large-Area ARROW

VCSOAs

From the above calculations, we have observed the following optical characteristics of ARROW VCSOAs:

- At low $P_{I,ml}$ ($\leq -50\text{dBm}$), the cavity resonance, $\lambda_{p,ml}$, of ARROW will vary with J due to the effects of thermal lensing. The shift of cavity resonance increases $G_{r,11}$ (reduces $G_{r,01}$) for a fixed wavelength and hence, de-stabilizes the amplified output signal of ARROW VCSOAs.
- At high $P_{I,ml}$ ($> -20\text{dBm}$), the effects of SHB and thermal lensing accelerate the saturation of $G_{r,01}$ but $G_{r,11}$ is less affected. Hence, this deteriorates the stability of the amplified output signal of ARROW VCSOAs.

These indicated that the optical characteristics of ARROW VCSOAs (although their optical characteristics are improved over the conventional index-guided VCSOAs) could be deteriorated by the presence of SHB and thermal lensing. Hence, a new design of ARROW is required to be developed for further improvement in the optical characteristics of ARROW VCSOAs.

In our earlier study of ARROW VCSELs, we have proposed a design rule to maximize the radiation loss margin between LM_{01} and LM_{11} . This can also be applied to design ARROW VCSOAs because the corresponding amplifier gain

margin $G_{r,01} - G_{r,11}$ can be maximized. The corresponding design procedures can be summarized as follows:

- i) For a fixed value of d_1 , corresponding values of s and d_2 are obtained to minimize the radiation loss of LM_{01} .
- ii) The value of d_2 found in step i) is then kept constant but the value of s is varied such that the radiation loss margin, the difference between the radiation loss of LM_{01} and the mode with the 2nd lowest radiation loss (i.e., usually LM_{11}), is maximized.

Through step i) the radiation loss of LM_{01} is kept low therefore allowing a low J_{th} . Step ii) maximizes the suppression of higher order modes. The value of s does not affect the radiation loss of LM_{01} significantly.

We have tried to apply this method to design ARROW VCSOAs. However, we found that this method is not suitable to achieve large $G_{r,01} - G_{r,11}$ in ARROW VCSOAs with $d_1 > 20 \mu\text{m}$. This is because step ii) cannot be realized for a sufficiently large radiation loss margin for a chosen value of d_1 . The limitation of the design rule can be resolved by swapping the order of the two steps. The new design procedures can be summarized as follows:

- i) For a fixed value of d_1 , find a corresponding combination of s and d_2 , which can produce the largest radiation loss margin.
- ii) Check whether the combination of (s, d_2) obtained in step i) is able to provide an acceptable low radiation loss in LM_{01} . If (s, d_2) is unable to satisfy the LM_{01} radiation loss requirement, choose

another (s, d_2) in the vicinity of that obtained from step i) on the s - d_2 plane (i.e. the area where the points may obtain the largest radiation loss margin) which can meet both the requirements of a low radiation loss in LM_{01} and a large radiation loss margin. It should be noted that the choice of (s, d_2) would not give the lowest radiation loss in LM_{01} or the largest radiation loss margin.

Hence, the chosen values will maximize the value of $G_{r,01} - G_{r,11}$ so that higher-order transverse cavity modes will not be excited by the amplification process.

Figure 6.8 plots the radiation loss margin of ARROW VCSOA with d_1 equal to 12 μm , 20 μm , 30 μm and 50 μm . Several combinations of (s, d_2) that correspond to the largest radiation loss margin are recorded. It is found that optimal combinations of (s, d_2) are (2.12 μm , 3.96 μm), (1.05 μm , 5.92 μm), (2.4 μm , 0.98 μm), (2.39 μm , 1.25 μm) for ARROW VCSOA with d_1 equal to 12 μm , 20 μm , 30 μm , 50 μm , respectively. From our calculations, we adjusted the value of s to maximize the radiation loss of LM_{11} , and at the same time maintain a reasonably low radiation loss of LM_{01} . This is done by scanning a range of s and d_2 to search for an optimal point. As a result, the values of s and d_2 are found to be neither odd integer number of quarter lateral waves nor integer number of half lateral waves.

The optical characteristics of ARROW VCSOAs with dimensions obtained from Figure 6.8 are studied. In Figure 6.9, the values of $d_1 = 12 \mu\text{m}$, $s = 2.12 \mu\text{m}$ and $d_2 = 3.96 \mu\text{m}$ are assumed in the calculation. At $J = 0.98 \times J_{th}$, it is shown that $G_{r,11}(\lambda_{p,11})$ is significantly suppressed, with $G_{r,11}(\lambda_{p,11}) \sim 35\text{dB}$ lower

Figure 6.8 Radiation loss margin between LM_{01} and the next lowest-loss transverse mode versus s and d_2 for ARROW VCSOA with (a) $d_1 = 12$ μm, (b) $d_1 = 20$ μm, (c) $d_1 = 30$ μm, (d) $d_1 = 50$ μm.

than $G_{r,01}(\lambda_{p,01})$. This amount of suppression is much higher than that of the ARROW VCSOA designed by minimizing the radiation loss first (see Figure 6.2). The separation between the resonant wavelengths of LM_{01} and LM_{11} is also significantly enlarged (from ~ 0.7 nm in Figure 6.2a to ~ 1.1 nm in Figure 6.9a). If the VCSOA is operating at $\lambda_{p,01}$, $G_{r,11}$ can be limited to ~ 1.1 dB at $J = 0.98 \times J_{th}$. This presence of LM_{11} can almost be eliminated even at high J . Therefore, we have shown that under high J and $P_{I,01}$, using the new design

Figure 6.9 Amplifier gain versus (a) signal wavelength and, (b) pump current for an ARROW VCSOA with $d_1 = 12 \mu\text{m}$, $s = 2.12 \mu\text{m}$, $d_2 = 3.96 \mu\text{m}$. The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{th}$).

rule, the optical characteristics of ARROW VCSOAs have larger value of $G_{r,01} - G_{r,11}$ than that of the ARROW VCSOA designed with minimum radiation loss.

The influence of SHB and thermal lensing on $G_{r,m1}$ of the ARROW VCSOA designed with the new design rule is also investigated. Figure 6.10 shows the variations of N , δn_N , ΔT , δn_T , Δn and $|\psi_{m1}|^2$ with different value of J . The main difference between the design of minimum radiation loss and maximum radiation loss margin (see Figures 6.4 and 6.10) is that the variation of Δn versus r is smaller in the case of maximum radiation loss margin. The amplifier gain spectra of LM₀₁ and LM₁₁ (i.e., $G_{r,01}$ and $G_{r,11}$) with $J = 0.6$ and $0.98 \times J_{th}$ is

also shown in Figure 6.10f. The solid (dashed) lines show the results with (without) the consideration of SHB and thermal lensing. As the variation of Δn is reduced (when compared with Figure 6.4f), the shift of cavity resonance (i.e., $\lambda_{p,m1}$) is minimized while the radiation loss of LM_{11} is increased (i.e., the 4th lobe of the LM_{11} has magnitude compatible with that of the 1st lobe, see Figure 6.10e). Hence, the new design ensures LM_{11} to be highly suppressed.

The variations of N , δn_N , ΔT , δn_T , Δn and $|\psi_{m1}|^2$ with different values of $P_{I,m1}$ are shown in Figure 6.11. When compared with Figure 6.6, it is noted that the reduction of $G_{r,01}(\lambda_{p,01})$ with respect to the increase in $P_{I,01}$ is less significant while the value of $G_{r,11}$ is significantly suppressed. The saturation input power increases to more than -17 dBm. This is because $G_{r,01}$ and $G_{r,11}$ share a common pool of carrier inside the active layer. If $G_{r,11}$ is suppressed by the proper design, the influence of $P_{I,01}$ on $G_{r,01}$ will be less evident. We also calculated the optical characteristics of ARROW VCSOAs with $d_1 > 20$ μm and similar conclusion has been obtained from calculation. The results are therefore not repeated herein. We have hence, verified that the new design of ARROW can enhance the stability of single-spot amplified output-signal emission while minimizing the influence of SHB and thermal lensing.

Figure 6.10 Transverse distributions of (a) carrier concentration, (b) carrier-induced index change, (c) temperature and heat-induced index change, (d) total index change and (e) field intensity of LM_{01} and LM_{11} . The arrows indicate the increase of J (from 0.6, 0.8, to $0.98 \times J_{\text{th}}$). The ARROW VCSOA has dimensions of $d_1 = 12 \mu\text{m}$, $s = 2.12 \mu\text{m}$ and, $d_2 = 3.96 \mu\text{m}$.

Figure 6.11 Transverse distribution of (a) carrier concentration, (b) carrier-induced and heat-induced index changes, (c) total index change and, (d) field intensity versus input signal power. (e) Amplifier gain of LM_{01} and LM_{11} versus input signal power. The arrows indicate the increase of $P_{\text{I},01}$ (from -50 dBm to -10 dBm with 10 dBm interval). The ARROW VCSOA has dimensions of $d_1 = 12$ μm , $s = 2.12$ μm and, $d_2 = 3.96$ μm .

6.3.4 Gain, bandwidth and saturation power of ARROW

VCSOAs with different diameters

Figure 6.12a plots the amplifier gain and bandwidth of ARROW VCSOAs versus d_1 (i.e., from 12 to 50 μm). The other parameters used in the calculation are similar to that given in Figure 6.8. It is assumed that $J = 0.9 \times J_{\text{th}}$ and $P_{\text{I},01} = -50$ dBm in the study. From Figure 6.12a, it is shown that bandwidth and $G_{\text{r},01}$ are independent of d_1 . This is because the bandwidth is mainly determined by the reflectance of the top/bottom reflector ($R_{\text{t}}/R_{\text{b}}$) and $G_{\text{r},01}$ [1]. With the value of $R_{\text{t}}/R_{\text{b}}$ fixed and the value of $G_{\text{r},01}$ being nearly a constant, the bandwidth does not change for different dimensions of ARROW VCSOAs. However, experimental studies have shown that the gain and bandwidth of the amplifier increase significantly with the increase of d_1 [2]. From our studies, we noted that the increase in both amplifier gain and bandwidth is the result of the excitation of higher-order transverse modes. Hence, the gain and bandwidth of index-guided VCSOAs will increase with an increase of core diameter but this is achieved at the expense of an extremely unstable profile of the amplified output signal [2]. The variation of $G_{\text{r},11}(\lambda_{\text{p},01})$ and $G_{\text{r},11}(\lambda_{\text{p},11})$ with d_1 is also shown in Figure 6.12a. It is noted that although $G_{\text{r},11}(\lambda_{\text{p},01})$ and $G_{\text{r},11}(\lambda_{\text{p},11})$ increase with the increase of d_1 , $G_{\text{r},01}(\lambda_{\text{p},01}) - G_{\text{r},11}(\lambda_{\text{p},11}) > 8$ dB can still be obtained for $d_1 = 50$ μm . This will therefore ensure the stability of amplified output signal for large-area ARROW VCSOAs.

Figure 6.12b shows the saturation input power of ARROW VCSOAs versus d_1 . It is observed that the saturation input power increases with d_1 , and because the reflection amplifier gain is kept nearly a constant with the increase of d_1 , it

Figure 6.12 Variation of (a) amplifier gain and bandwidth and, (b) saturation power versus d_1 . The methods to measure bandwidth and saturation power are shown in (c) and (d), respectively.

is obvious the saturation output power will also increase with d_1 . If the total coupling loss of ARROW VCSOAs is ~ 7 dB, the saturation output power of a well-designed ARROW VCSOA can reach ~ -4.1 dBm for $d_1 = 12 \mu\text{m}$ and ~ -3.1 dBm for $d_1 = 50 \mu\text{m}$ (for LM_{01}), which is higher than the state of the art VCSOAs [10]. Hence, the saturation power of ARROW VCSOAs can be enhanced with the increase of d_1 , without sacrificing the stability of the amplified output signal.

6.4 Conclusions

In conclusion, the optical characteristics of ARROW VCSOAs are investigated theoretically. A simple self-consistent model, including the effects of SHB and thermal lensing, has been developed to analyze the stability of output amplified signal of ARROW VCSOAs. We have compared the optical characteristics of ARROW VCSOA to that of conventional index-guided VCSOAs. It is shown that the presence of ARROW can improve the stability of amplified output-signal emission, and without deteriorating the amplifier gain of the VCSOAs. In addition, a new design rule is proposed to optimize the dimensions of ARROW for maximizing the optical gain margin. We have shown that with the proper design of ARROW, the influence of SHB and thermal lensing on the stability of amplified output-signal emission of VCSOAs can be minimized. In addition, high saturation power can be achieved simultaneously in large-area ARROW VCSOAs.

REFERENCES

- [1] E. S. Bjorlin, T. Kimura, and J. E. Bowers, "Carrier-confined vertical-cavity semiconductor optical amplifiers for higher gain and efficiency," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 9, pp. 1374-1385, Sep-Oct 2003.
- [2] F. Marino and S. Balle, "Experimental study of a broad area vertical-cavity semiconductor optical amplifier," *Optics Communications*, vol. 231, pp. 325-330, Feb 15 2004.
- [3] D. L. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 38, pp. 1599-1606, Dec 2002.
- [4] A. Valle, "Selection and modulation of high-order transverse modes in vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 34, pp. 1924-1932, Oct 1998.
- [5] P. Royo, R. Koda, and L. A. Coldren, "Rate equations of vertical-cavity semiconductor optical amplifiers," *Applied Physics Letters*, vol. 80, pp. 3057-3059, Apr 29 2002.
- [6] S. F. Yu, *Analysis and design of vertical cavity surface emitting lasers*. New York: Wiley, 2003.
- [7] S. F. Yu, "Polarization selection in birefringent antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE Journal of Quantum Electronics*, vol. 39, pp. 1362-1371, Nov 2003.
- [8] Y. G. Zhao and J. G. Mcinerney, "Transient Temperature Response of Vertical-Cavity Surface-Emitting Semiconductor-Lasers," *IEEE Journal of Quantum Electronics*, vol. 31, pp. 1668-1673, Sep 1995.
- [9] T. Kimura, S. Bjorlin, J. Piprek, and J. E. Bowers, "High-temperature characteristics and tunability of long-wavelength vertical-cavity semiconductor optical amplifiers," *IEEE Photonics Technology Letters*, vol. 15, pp. 1501-1503, Nov 2003.
- [10] E. S. Bjorlin, T. Kimura, Q. Chen, C. Wang, and J. E. Bowers, "High output power 1540nm vertical cavity semiconductor optical amplifiers," *Electronics Letters*, vol. 40, pp. 121-123, Jan 2004.

CHAPTER 7

Discussion and Conclusion

High-power and stable single-mode operation of vertical-cavity surface-emitting lasers (VCSELs) and vertical-cavity semiconductor optical amplifiers (VCSOAs) are highly desired in numerous applications. Maximum output power of the VCSELs and VCSOAs can be scaled up by increasing the corresponding aperture size. However, large aperture size may lead to strong spatial-hole-burning (SHB) and thermal lensing, which will facilitate the excitation of high-order transverse modes, increase the sensitivity to external optical feedback, and invite other instability problems. Therefore, it may be difficult to achieve high-power and stable single-mode operation in large aperture VCSELs and VCSOAs. In this thesis, it is proposed to use anti-resonance reflecting optical waveguide (ARROW) to achieve stable single-mode operation at high power in large aperture VCSELs and VCSOAs. This is possible because the use of ARROW can purposely introduce radiation losses to the transverse optical modes of the devices. With suitable design of ARROW, radiation loss margin between fundamental and high-order transverse modes can be maximized so that only the fundamental transverse mode will be supported in large aperture devices even at high power operation.

A self-consistent laser model, which consists of two coupled rate equations of carrier concentration and photon density, was developed to study the multi-transverse mode characteristics of ARROW VCSELs. In addition, the influence of SHB and thermal lensing effects was taken into consideration. The non-uniform distribution of the transverse modes was also calculated by the transfer-matrix method. Using this model, the above-threshold characteristics of ARROW VCSELs were investigated. It was found that the thermal lensing effect is the main cause of the excitation of higher order transverse modes for the devices in CW operation. In pulsed operation, the excitation of higher order transverse modes is mainly dependent on the influence of SHB. Based on the above studies, a design method was proposed to optimize the radiation loss margin between the fundamental and high order transverse modes in ARROW VCSELs. As a result, suppression of higher-order transverse modes can be easily achieved in large aperture ARROW VCSELs.

The proposed laser model was extended to study the transient response of ARROW VCSELs under the influence external optical feedback. In addition, the mechanism of polarization switching was investigated by the laser model with the influence of birefringence (i.e., induced by anisotropic strain and stress inside the device structure) taken into consideration. It was shown that

- if the radiation loss margin between the fundamental and high order transverse modes can be maximized by the proper design of ARROW structure, stabilize high-power single-mode operation of VCSELs can be maintained even under strong external feedback;

- if the radiation loss margin between the two polarizations can be maximized, suppression of polarization switching can be achieved even under the influence of thermal lensing effect.

Hence, it is believed that high-power and stable single-mode operation of ARROW VCSELs can be achieved provided that the ARROW structure is carefully designed.

A self-consistent amplifier model, which takes into the consideration of SHB and thermal lensing effects, was also developed to study the stability of output signal of ARROW VCISOAs. It was found that the ARROW VCISOAs can achieve stability single-mode emission at power much higher than that of the conventional index-guided VCISOAs. This is because the presence of ARROW can effectively suppress the increase of amplifier gain of the high order transverse modes due to the influence of SHB and thermal lensing effects. A design rule for ARROW VCISOAs was also proposed to optimize the stability of output signal. This can be done by maximizing the radiation loss margin between the fundamental and next high order transverse modes. As a result, the amplifier gain, bandwidth and saturation power of the ARROW VCISOAs can be significantly improved over the conventional VCISOAs.

In conclusion, the optical characteristics of ARROW VCSELs and VCISOAs were studied. It was shown that stable single-mode and high-power emission can be obtained from large aperture VCSELs and VCISOAs if the corresponding ARROW is properly designed. In addition, the radiation loss margin of ARROW is the most important factor in determining the optical performance of the devices.

Author's Publications

Regular Journals

- [1] N. S. Chen and S. F. Yu, "Design and analysis of large-area vertical-cavity semiconductor optical amplifiers with anti-resonant reflecting optical waveguide," *Journal of Lightwave Technology*, vol. 24, pp. 526-535, Jan 2006.
- [2] C. Yuen, S. F. Yu, E. S. P. Leong, H. Y. Yang, S. P. Lau, N. S. Chen, and H. H. Hng, "Low-loss and directional output ZnO thin-film ridge waveguide random lasers with MgO capped layer," *Applied Physics Letters*, vol. 86, Jan 2005.
- [3] C. W. Tee, S. F. Yu, and N. S. Chen, "Transverse-leaky-mode characteristics of ARROW VCSELs," *Journal of Lightwave Technology*, vol. 22, pp. 1797-1804, Jul 2004.
- [4] N. S. Chen and S. F. Yu, "Transient response of ARROW VCSELs under external optical feedback," *IEEE Photonics Technology Letters*, vol. 16, pp. 1610-1612, Jul 2004.
- [5] N. S. Chen, S. F. Yu, and C. W. Tee, "Suppression of polarization switching in birefringent antiresonant reflecting optical waveguide vertical-cavity surface-emitting lasers," *IEEE Photonics Technology Letters*, vol. 16, pp. 711-713, Mar 2004.

Conference Papers

- [1] N.S. Chen and S.F. Yu, 'Numerical Study of Large-area Anti-Resonant Reflecting Optical Waveguide Vertical-Cavity Semiconductor Optical Amplifiers', *Proceedings of the 5th International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD'05)*, pp. 123-124, 2005.
- [2] S.F. Yu and N.S. Chen, "Characteristics of ARROW VCSELs under External Optical Feedback", *Proceedings of the 4th International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD '04)*, pp. 47-48, 2004.