

**DESIGN OF EFFICIENT OPTICAL AND ELECTRICAL
PUMPING CONFIGURATIONS FOR SEMICONDUCTOR
OPTICAL AMPLIFIERS AND LASERS**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2023**

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PUMPING CONFIGURATIONS FOR SEMICONDUCTOR
OPTICAL AMPLIFIERS AND LASERS**

by

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submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2023

CERTIFICATE

*This is to certify that the thesis titled "**Design of Efficient Optical and Electrical Pumping Configurations for Semiconductor Optical Amplifiers and Lasers**", being submitted by **Mr. Nithin V** to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which to the best of my knowledge has reached the requisite standard.*

The material contained in the thesis has not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

First, I would like to express my profound gratitude to Prof. M. R. Shenoy, who not only introduced me to the area of semiconductor optoelectronics through his excellent teaching skills but was also immensely supportive throughout my Ph.D. journey. His vast and penetrative understanding of the subject enabled me to grasp the significance of the minutest aspects of the research, which, otherwise appears trivial and glossed over. He also taught me scientific writing skills and how to present the research output in a simple and concise manner. Throughout this challenging journey, his wise counsel and optimism gave me invaluable encouragement to continue without losing hope. I can never forget his kindness and patience towards me when my health frequently suffered during the cold winters of Delhi. He helped me approach life and research holistically and not just stop at a particular aspect. He has not only helped me to develop myself as a professional academician but also shaped me to be a better human being.

I want to express my warm and sincere thanks to my SRC members, Prof. R.K. Varshney, Prof. Alok Sinha, and Prof. Abhishek Dixit, whose pointed queries and suggestions helped to improve my research work. I also want to express my sincere thanks to my course teachers Prof. K. Thyagarajan, Prof. Arun Kumar, Prof. B.P. Pal, and Prof. Anurag Sharma. They taught me different areas of photonics, ranging from non-linear optics, integrated optics, and fiber optics to numerical methods in photonics.

I am also thankful to Dr. Yogesh Kumar, my senior at IIT Delhi and with Defense Research and Development Organization (DRDO), for his counsel on various areas of my research. I consider myself fortunate for the opportunity to work closely with him. He has invaluable added to the quality of the thesis with his specialized inputs and suggestions.

I also express my sincere gratitude to Mr. Animesh Raj and Ms. Deepti Jain, project students in Fiber Optics Lab. Their suggestions offered me a different perspective on numerical simulation and waveguide design. I am also indebted to the lab superintendent, Mr. Vijay Sharma, for his help during the experimental study. His knowledge and experience in handling lab equipments have helped me conduct experiments smoothly.

I want to thank my Family members, who have stood by me as a strong pillar in this arduous journey. I am thankful to my parents, Sh. Satyashankar and Smt. Vijayashree, for their love, blessings, and understanding. I am grateful to my wife, Ms. Lakshmi Kavya, who understood my professional needs and commitments, and supported me constantly.

Nithin V

ABSTRACT

Semiconductor optical amplifiers (SOAs) and semiconductor lasers are key components in optical communication and signal processing. Conventionally, these devices are electrically-biased to inject the carriers into the active region. However, there is a growing need for optically-controlled photonic devices to enable an all-optical platform for signal processing. Optical pumping provides optical-to-optical gain control and thus avoids slower electrical-to-optical conversion in electrically-biased devices. Since optical pumping doesn't require a p-n junction, high-purity (undoped) materials can be employed, which minimizes optical losses.

Optical pumping is a well-established scheme in erbium-doped fiber amplifiers (EDFAs), where the pump is injected directly along the doped fiber in an end-pumping configuration. However, the direct end-pumping scheme is highly-inefficient in the case of SOAs and semiconductor lasers, because semiconductors have a high absorption coefficient. Therefore, the entire pump power would be absorbed within a short distance from the injection end, with the latter portion of the active region remaining unpumped. Optical pumping schemes from the top/side of the semiconductor active region have also been investigated. Since the cross-section dimensions of the active region are small (typically $< 2 \mu\text{m}$), only a fraction of the pump power is absorbed. Moreover, due to the requirement of bulk components for light illumination, such optical pumping scheme through external illumination is incompatible with photonic integrated circuits (PICs).

This thesis presents our investigation on the development of novel optical pumping configurations through a transverse waveguide-coupling scheme to achieve efficient and compact optically-pumped SOA (OP-SOA) and optically-pumped semiconductor laser. In the proposed waveguide-coupled optical pumping scheme, the optical pump is coupled into the

‘active waveguide’ from an adjacent channel waveguide, called ‘pump waveguide’. Through numerical analysis, we show that an efficient transfer of the pump power can be achieved in a directional coupler configuration, which comprises of a lossless input waveguide (pump waveguide) and a highly absorbing waveguide (active waveguide). An appropriate design of the coupled-waveguide structure results in efficient optical pumping with a unidirectional transfer of pump power; further, it is also possible to maintain a desired pump-power transfer profile in the absorbing waveguide to achieve optimal performance of the device.

The optical pumping in SOA is shown through two different coupled-waveguide structures: buried channel coupled-waveguide and ridge-waveguide coupler. It is found that by suitable choice of materials and waveguide design, single transverse-mode operation and low polarization dependence could be achieved in OP-SOA based on a ridge-waveguide coupler. The proposed OP-SOA is an $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ -based heterostructure device with a pump at 1310 nm wavelength and amplification in the C-band wavelength range. The optical pump can be coupled into the pump waveguide through a separate fiber pigtail, similar to how the signal is coupled to the active waveguide in a commercially available SOA. Thus, the OP-SOA would be a stand-alone 3-port integrated optical device. In order to simulate the performance characteristics of OP-SOA, we suitably modify the well-established Connelly’s numerical model for conventional electrically-biased SOA. The gain characteristics of OP-SOA are found to be qualitatively similar to that of conventional electrically-biased SOA.

We also propose an integrated design of an in-plane optically-pumped edge-emitting ridge-waveguide semiconductor laser without any bulk components. The laser device is based on $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ heterojunction, with a pump at 1310 nm wavelength and lasing around 1550 nm. Since a semiconductor laser is essentially an SOA with optical feedback, the output characteristics of the proposed laser device are simulated by a modified numerical model of SOA by incorporating the lasing process. The simulated output characteristics are found to be

consistent with the laser theory. A high pump power conversion efficiency (ratio of output laser power to input pump power) is obtained under optimum operating conditions for the chosen device parameters. The proposed optically-pumped semiconductor laser could be a 2-port fiber pig-tailed integrated optical device without needing any bias current.

We also explore the optimization of the multi-segment configuration of SOA for wavelength division multiplexing (WDM) applications. The design and characteristics of a two-segment SOA are presented, whose segment length and bias current ratio are optimized. We show that the gain-spread and noise figure can be reduced by tailoring of the longitudinal carrier density profile. The differential gain among the channels is also reduced due to the contrasting gain and transmission spectra of the two gain segments.

Finally, we present our experimental studies on the optical pumping of a conventional SOA. First, we experimentally study the gain and absorption characteristics of SOA. Then, we setup the co-propagating and the counter-propagating configuration for optical pumping in SOA, and study the gain characteristics. We also experimentally show that the optical pumping of SOA through the end-pumping scheme is inefficient.

सार

सेमीकंडक्टर ऑप्टिकल एम्पलीफायर (सेऑए) और सेमीकंडक्टर लेजर ऑप्टिकल संचार और सिग्नल प्रोसेसिंग में प्रमुख घटक हैं। परंपरागत रूप से, इन उपकरणों को सक्रिय क्षेत्र में वाहक को इंजेक्ट करने के लिए विद्युत-पक्षपाती किया जाता है। हालांकि, सिग्नल प्रोसेसिंग के लिए एक ऑल-ऑप्टिकल प्लेटफॉर्म को सक्षम करने के लिए ऑप्टिकल रूप से नियंत्रित फोटोनिक उपकरणों की बढ़ती आवश्यकता है। ऑप्टिकल पंपिंग ऑप्टिकल-टू-ऑप्टिकल लाभ नियंत्रण प्रदान करता है और इस प्रकार विद्युत-पक्षपाती उपकरणों में धीमी विद्युत-टू-ऑप्टिकल रूपांतरण से बचा जाता है। चूंकि ऑप्टिकल पंपिंग के लिए पी-एन जंक्शन की आवश्यकता नहीं होती है, इसलिए उच्च शुद्धता (अवांछित) सामग्री को नियोजित किया जा सकता है, जो ऑप्टिकल नुकसान को कम करता है।

ऑप्टिकल पंपिंग अर्बियम-डोपड फाइबर एम्पलीफायरों में एक अच्छी तरह से स्थापित योजना है, जहां पंप को एक एंड-पंपिंग कॉन्फिगरेशन में सीधे डोपड फाइबर के साथ इंजेक्ट किया जाता है। हालांकि, सेऑए और अर्धचालक लेजरों के मामले में प्रत्यक्ष अंत-पंपिंग योजना अत्यधिक अक्षम है, क्योंकि अर्धचालकों में उच्च अवशोषण गुणांक होता है। इसलिए, पूरे पंप की शक्ति इंजेक्शन के अंत से थोड़ी दूरी के भीतर अवशोषित हो जाएगी, सक्रिय क्षेत्र के बाद के हिस्से को पंप नहीं किया जाएगा। सेमीकंडक्टर सक्रिय क्षेत्र के ऊपर / किनारे से ऑप्टिकल पंपिंग योजनाओं की भी जांच की गई है। चूंकि सक्रिय क्षेत्र के क्रॉस-सेक्शन आयाम छोटे हैं (आमतौर पर $< 2 \mu\text{m}$), पंप शक्ति का केवल एक अंश अवशोषित होता है। इसके अलावा, प्रकाश रोशनी के लिए थोक घटकों की आवश्यकता के कारण, बाहरी

रोशनी के माध्यम से इस तरह की ऑप्टिकल पंपिंग योजना फोटोनिक एकीकृत सर्किट के साथ असंगत है।

एसओए में ऑप्टिकल पंपिंग को दो अलग-अलग युग्मित-वेवगाइड संरचनाओं के माध्यम से दिखाया गया है: दफन चैनल युग्मित-वेवगाइड और रिज-वेवगाइड कपलर। यह पाया गया है कि सामग्री और वेवगाइड डिजाइन की उपयुक्त पसंद से, एकल ट्रांसवर्स-मोड ऑपरेशन और कम ध्रुवीकरण निर्भरता को रिज-वेवगाइड कपलर के आधार पर ओपी-एसओए में प्राप्त किया जा सकता है। प्रस्तावित ओपी-एसओए एक $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ -आधारित हेटरोस्ट्रक्चर डिवाइस है, जिसमें 1310 एनएम तरंगदैर्घ्य पर एक पंप है और सी-बैंड तरंगदैर्घ्य रेंज में प्रवर्धन है। ऑप्टिकल पंप को एक अलग फाइबर पिगटेल के माध्यम से पंप वेवगाइड में जोड़ा जा सकता है, जो कि व्यावसायिक रूप से उपलब्ध एसओए में सक्रिय वेवगाइड के लिए सिग्नल के समान है। इस प्रकार, ओपी-एसओए एक स्टैंड-अलोन 3-पोर्ट एकीकृत ऑप्टिकल डिवाइस होगा। ओपी-एसओए की प्रदर्शन विशेषताओं का अनुकरण करने के लिए, हम पारंपरिक विद्युत-पक्षपाती एसओए के लिए अच्छी तरह से स्थापित कॉनेलली के संख्यात्मक मॉडल को उपयुक्त रूप से संशोधित करते हैं। ओपी-एसओए की लाभ विशेषताओं को गुणात्मक रूप से पारंपरिक विद्युत-पक्षपाती एसओए के समान पाया जाता है।

हम किसी भी थोक घटकों के बिना एक इन-प्लेन ऑप्टिकली-पंप एज-उत्सर्जक रिज-वेवगाइड सेमीकंडक्टर लेजर के एकीकृत डिजाइन का भी प्रस्ताव करते हैं। लेजर डिवाइस $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ हेटरोजंक्शन पर आधारित है, जिसमें 1310 एनएम तरंगदैर्घ्य का एक पंप है और लगभग 1550 एनएम

लेसिंग है। चूंकि एक अर्धचालक लेजर अनिवार्य रूप से ऑप्टिकल प्रतिक्रिया के साथ एक सेऑए है, प्रस्तावित लेजर डिवाइस की आउटपुट विशेषताओं को लेसिंग प्रक्रिया को शामिल करके सेऑए के एक संशोधित संख्यात्मक मॉडल द्वारा अनुकरण किया जाता है। सिमुलेटेड आउटपुट विशेषताओं को लेजर सिद्धांत के अनुरूप पाया जाता है। एक उच्च पंप पावर रूपांतरण दक्षता (आउटपुट लेजर पावर से इनपुट पंप पावर का अनुपात) चुने हुए डिवाइस मापदंडों के लिए इष्टतम ऑपरेटिंग परिस्थितियों में प्राप्त की जाती है। प्रस्तावित ऑप्टिकली-पंप अर्धचालक लेजर किसी भी पूर्वाग्रह वर्तमान की आवश्यकता के बिना एक 2-पोर्ट फाइबर सुअर-पूछ एकीकृत ऑप्टिकल डिवाइस हो सकता है।

हम तरंग दैर्घ्य विभाजन मल्टीप्लेक्सिंग (डब्ल्यूडीएम) अनुप्रयोगों के लिए एसओए के बहु-सेगमेंट कॉन्फिगरेशन के अनुकूलन का भी पता लगाते हैं। एक दो-खंड सेऑए के डिजाइन और विशेषताओं को प्रस्तुत किया जाता है, जिसका खंड लंबाई और पूर्वाग्रह वर्तमान अनुपात अनुकूलित किया जाता है। हम दिखाते हैं कि लाभ-प्रसार और शोर आंकड़ा अनुदैर्घ्य वाहक घनत्व प्रोफाइल के सिलाई द्वारा कम किया जा सकता है। दोनों लाभ खंडों के विपरीत लाभ और संचरण स्पेक्ट्रा के कारण चैनलों के बीच अंतर लाभ भी कम हो जाता है।

अंत में, हम एक पारंपरिक सेऑए के ऑप्टिकल पंपिंग पर हमारे प्रयोगात्मक अध्ययन प्रस्तुत करते हैं। सबसे पहले, हम प्रायोगिक रूप से सेऑए के लाभ और अवशोषण विशेषताओं का अध्ययन करते हैं। फिर, हम एसओए में ऑप्टिकल पंपिंग के लिए सह-प्रचार और काउंटर-प्रचार कॉन्फिगरेशन

को सेटअप करते हैं, और लाभ विशेषताओं का अध्ययन करते हैं। हम प्रयोगात्मक रूप से यह भी दिखाते हैं कि एंड-पंपिंग योजना के माध्यम से एसओए का ऑप्टिकल पंपिंग अक्षम है।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
Abstract (Hindi)	vii
Contents	xi
List of Figures	xv
List of Tables	xxii
List of Abbreviations	xxiii
1 Introduction.....	1
1.1 Semiconductor optical amplifier and laser	1
1.2 Coupled-waveguide structures	2
1.3 Motivation and objectives of the thesis	4
1.4 Organization of the thesis	6
2 Semiconductor Optical Amplifiers and Lasers	8
2.1 Introduction.....	8
2.2 Optical processes in semiconductors	9
2.3 Optical amplification in semiconductors	10
2.4 Double heterostructure.....	11
2.5 Difference between the structure of SOA and semiconductor laser	12
2.6 Connelly's steady-state model for SOA	13
2.6.1 Material gain coefficient.....	14

2.6.2 Carrier density rate equation	16
2.7 Simulation results of SOA	20
2.8 Modified model for semiconductor laser	22
2.9 Simulation results of semiconductor laser	23
2.10 Multi-section semiconductor laser	26
2.11 Summary	28
3 Study of Coupled Waveguide Structures with Absorbing Waveguides	29
3.1 Introduction.....	29
3.3 Simulation results.....	32
3.3.1 Non-absorbing coupled-waveguide structure	33
3.3.2 Weakly-absorbing coupled-waveguide structure.....	34
3.3.3 Strongly-absorbing coupled-waveguide structure	34
3.4 Coupled-waveguide structure for fluorescence sensing application.....	35
3.5 Summary	38
4 Optical Pumping of SOA through Buried-channel Coupled-waveguide Configuration	39
4.1 Introduction.....	39
4.2 Optical pumping scheme.....	40
4.3 Choice of pump wavelength	42
4.4 Modelling the OP-SOA.....	44
4.5 Results and discussion	46
4.6 Summary	51

5 Efficient Optically-pumped SOA and Semiconductor Laser through a Ridge-waveguide Coupler Configuration	53
5.1 Introduction.....	53
5.2 Scheme of optical pumping through ridge-waveguide coupler in SOA	54
5.3 Choice of materials	56
5.4 Coupling characteristics.....	59
5.5 Results and discussion of OP-SOA through ridge-waveguide coupler	60
5.6 Scheme of the optically-pumped edge-emitting semiconductor laser	64
5.7 Numerical modelling of optically-pumped semiconductor laser.....	67
5.8 Results and discussion of optically-pumped semiconductor laser.....	69
5.9 Summary	73
6 Minimizing the Gain Variation in SOA using Optimized Multi-section Configuration for WDM Applications	74
6.1 Introduction.....	74
6.2 Amplifier characteristics of WDM signals in a conventional SOA.....	76
6.2 Optimizing gain variation and noise figure in multi-segment SOA	80
6.4 Optimized 2-segment SOA.....	83
6.5 Summary	87
7 Experimental Efforts: Optical Pumping in a Conventional SOA	89
7.1 Introduction.....	89
7.2 Characterization of SOA.....	89
7.3 Absorption spectrum of SOA in the C-band.....	93

7.4 Optical pumping in SOA	95
7.5 Summary	96
8 Summary and Future Scope	98
References.....	100
Publications.....	112
Authors Brief Biography.....	114

List of Figures

2.1: Schematic showing the process of (a) absorption, (b) spontaneous emission, and (c) stimulated emission in a semiconductor through E-k diagram.....	9
2.2: Schematic showing optical amplification in semiconductors through electrical/optical pumping	11
2.3: Schematic showing the cross-section of a double-heterostructure; the bandgap energy and refractive index profiles are shown on the right	12
2.4: Schematic showing a (a) longitudinal cross-section of an SOA and (b) longitudinal cross-section of a semiconductor laser	13
2.5: Schematic view of the longitudinal sections of length Δz along the SOA	14
2.6: Flowchart for numerical solution of SOA	19
2.7: SOA fiber-to-fiber gain and noise figure vs. bias current for low (-40 dBm) and high input signal power (-10 dBm)	21
2.8: Gain spectra and noise figure spectra in C-band for low (-40 dBm) and high input signal power (-10 dBm).....	22
2.9: Schematic showing longitudinal cross-section of a semiconductor laser.....	22
2.10: Variation of the output power with the number of iterations	24
2.11: Variation of the output power of the peak longitudinal mode with the bias current	25
2.12: Output power distribution in longitudinal modes at a bias current of 150 mA	25
2.13: Tuning of the wavelength of the lasing mode with the bias current.....	26
2.14: Output power distribution among the prominent longitudinal modes of laser for single-section configuration and three-section configurations with bias currents $I_1 = I_2 = 37.5$ mA, I_3	

= 75 mA. The total bias current for both cases is 150 mA. The inset figure shows a schematic of the 3-segment configuration27

3.1: Schematic of a typical coupled-waveguide structure32

3.2: Longitudinal power distribution profile in WG1 (solid line) and WG2 (dashed line) for non-absorbing coupled-waveguides ($k_1 = k_2 = 0$), when all the input power (at $z = 0$) is in WG133

3.3: Longitudinal power distribution profile in WG1 (solid line) and WG2 (dashed line) for (a) one non-absorbing and one weakly-absorbing coupled waveguides ($k_1 = 0, k_2 = 10^{-5}$) and (b) both weakly-absorbing coupled-waveguides ($k_1 = k_2 = 10^{-5}$).....34

3.4: Longitudinal power distribution profile in WG1 (solid line) and WG2 (dashed line) for (a) one non-absorbing and one strongly absorbing coupled waveguides ($k_1 = 0, k_2 = 10^{-4}$) and (b) both strongly-absorbing coupled-waveguides ($k_1 = k_2 = 10^{-4}$).....35

3.5: (a) Conventional scheme of evanescent wave-based fluorescent sensor, and (b) Proposed scheme of evanescent wave-based fluorescent sensor.....35

3.6: Schematic of a typical coupled-waveguide structure that may be used for a fluorescent sensor37

3.7: Pump power distribution along the sensing waveguide for three different cases: (i) uniform inter-waveguide separation of $3.3 \mu\text{m}$, (ii) uniform inter-waveguide separation of $5.45 \mu\text{m}$, and (iii) linearly decreasing inter-waveguide separation, $d = 5.45 \mu\text{m}$ at $z = 0$ and $d = 3.3 \mu\text{m}$ at $z = 10 \text{ mm}$37

3.8: Image map of the TE polarized electric field (x-component) in coupled-structure when a modal field is launched into the pump waveguide.....37

4.1: (a) Scheme of pumping in a conventional SOA, (b) Scheme for direct-end pumping of an SOA, and (c) Proposed scheme for optically pumped SOA (OP-SOA). P_{in} is the weak signal input, and P_{out} is the amplified output.....	40
4.2: Top-view of the proposed scheme of optical pumping, showing evanescent wave coupling all along the length.....	41
4.3: Absorption/Gain spectra of InGaAsP for three different values of the carrier density	43
4.4: Normalized pump power distribution along the SOA for direct end-pumping (solid) and waveguide coupled pumping (dashed) in the case of counter-directional pumping.....	44
4.5: Carrier distribution along the active waveguide for the case of direct-end pumped SOA and waveguide coupled 3-port OP-SOA with 100 mW pump power at 1310 nm. Different carrier distribution profiles in the active waveguide of the OP-SOA are due to the different pump power transfer profiles (PPTP)	47
4.6: Carrier distributions along the active waveguide in 3-port OP-SOA with 100 mW pump power for different input signal powers ($P_{s in}$).....	47
4.7: ASE spectra at the output of the 3-port OP-SOA for three different PPTPs.....	48
4.8: Gain variation with input pump power in the OP-SOA for three different input signal powers.....	49
4.9 Gain spectra of the OP-SOA with three different levels of optical pumping	50
4.10 Output saturation characteristics of the OP-SOA for three different pump powers.....	51
5.1: Schematic of the proposed OP-SOA in which pumping of the active waveguide takes place through evanescent wave coupling in the ridge-waveguide coupler	54

5.2: Top-view of the proposed OP-SOA showing the design of the coupled-waveguide configuration; pump power is coupled into the pump waveguide at $z = 0$ and transferred to the active waveguide through evanescent wave coupling	55
5.3: Variation of the material absorption coefficient, α_m at 1310 nm (dotted line) and gain coefficient, g_m at 1550 nm (solid line) with y composition of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ at the carrier density $N = 2 \times 10^{24} \text{ m}^{-3}$	57
5.4: Dispersion curves for the materials used in the epilayer, pump waveguide, active waveguide, and the overlay.....	58
5.5: Pump power profile in the active and the pump waveguides for two different absorption coefficients of the active waveguide material (α_1 and α_2) at the pump wavelength, when the pump is injected at $z = 0$; the pump waveguide is assumed to be non-absorbing	60
5.6: Gain variation with input pump power in the 3-port OP-SOA for different input signal powers (P_{in}^{sig}).	61
5.7: Gain spectra of the 3-port OP-SOA for three different pump powers (P_{in}^{pump}) for an input signal power of -40 dBm.....	62
5.8: Output saturation characteristics of the 3-port OP-SOA for three different input pump powers (P_{in}^{pump}).	62
5.9: Noise figure spectrum of the 3-port OP-SOA for three different pump powers (P_{in}^{pump})	63
5.10: Plot of noise figure vs. input signal power for three different pump powers	64
5.10: Schematic of the proposed optically-pumped edge-emitting semiconductor laser in which pumping takes place through evanescent wave coupling in the ridge-waveguide coupler	65

5.11 The transverse cross-section of the coupled-waveguide structure showing the materials and the dimension involved. The separation between the waveguides is linearly decreased from 1 μm at $z = 0$ to 0.5 μm at $z = 500 \mu\text{m}$	66
5.12: Plot of the peak wavelength (i.e., wavelength corresponding to the peak longitudinal mode) at the laser output with y composition.....	66
5.13: The steady-state power profiles of the forward-propagating lasing mode (P_{LW}^+), the backward-propagating lasing mode (P_{LW}^-) and the pump power (P_{AW}^P) along the active waveguide of the optically-pumped semiconductor laser for an input pump power of 100 mW. The inset figure shows the carrier density distribution along the active waveguide	70
5.15: Variation of output power with the input pump power for three different cases of pump power absorption.....	72
6.1 (b): Plot of gain variation and average noise figure of channels with the length of the SOA for an eight-channel WDM system (see Fig. 6.1 (a))	78
6.2: The variation of gain and noise figure of 8 WDM channels with input signal power for a bias current of 100 mA and SOA length of 300 μm	79
6.3: The variation of gain and noise figure of 8 WDM channels with bias current for an input signal power of -20 dBm.....	80
6.4: Schematics of (a) Conventional SOA with a single length segment, (b) A 3-segment SOA with segment lengths of 100 μm each and independent bias currents, and (c) A 3-segment SOA showing the bias current split into three segments through three suitable resistors	81
6.5: Two-segment SOA with segment lengths of 100 μm and 200 μm	83
6.6 (a): Evolution of the signal power in 8 WDM channels along the length of (a) conventional SOA.....	84

6.6 (b): Evolution of the signal power in 8 WDM channels along the length of optimized two-segment SOA with the current ratio of 15:2. The total bias current of the SOA is 100 mA, and the input signal power is -40 dBm in each channel, for both cases shown in (a) and (b) above	84
6.7: Longitudinal profile of carrier density in a conventional SOA (solid line) and in the corresponding two-segment SOA with a current ratio of 15:2 (dotted line). The bias current is 100 mA, and the input signal power is -40 dBm per channel.....	85
6.8: Gain spectrum in a conventional SOA (solid line) and in the corresponding two-segment SOA with a current ratio of 15:2 (dotted line). The bias current is 100 mA, and the input signal power is -40 dBm per channel.	86
6.9: Gain spectrum in the first (dashed line) and the second segments (solid line) in the two-segment SOA with a current ratio of 15:2. The bias current is 100 mA, and the input signal power is -40 dBm per channel.	86
7.1: Schematic of the experimental setup to characterize SOA.....	90
7.2: Snapshot of the experimental setup used to determine the gain characteristics of SOA..	90
7.3: SOA gain spectra for different values of bias current	92
7.4: Plot of SOA gain spectra with bias current for three different input signal powers.....	92
7.5: Output power saturation characteristics for three different bias currents.	93
7.6: Absorption spectra of SOA for different bias currents below the transparency	94
7.7: Schematic of the experimental setup for co-propagation pumping of SOA.....	95
7.8: Schematic of the experimental setup for counter-propagation pumping of SOA.....	95

7.9: Variation of fiber-to-fiber gain of SOA with optical pump power in co- and counter-propagating pumping scheme. The signal is at a wavelength of 1550 nm with an input power of 54 μ W.96

List of Tables

2.1: Symbols and numerical values of the parameters used for simulation.....	16
5.1: Waveguide parameters used in the design of the proposed device.....	56
6.1. SOA device parameters used in the simulation	76
6.2. Gain and noise characteristics of 8 WDM channels in a 3-segment SOA for different bias current ratios, with a total bias current of 100 mA	82

List of Abbreviations

ASE	Amplified Spontaneous Emission
BPM	Beam Propagation Method
CB	Conduction Band
EDFA	Erbium Doped Fibre Amplifier
FD-BPM	Finite Difference Beam Propagation Method
OP-SOA	Optically-pumped Semiconductor Amplifier
PICs	Photonic Integrated Circuits
PPTP	Pump Power Transfer Profile
SOA	Semiconductor Optical Amplifier
TE	Transverse Electric
VB	Valence Band
WDM	Wavelength Division Multiplexing
WG	Wave Guide