Device building blocks for photonic integration : design and process

Lee, Chee Wei

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DEVICE BUILDING BLOCKS FOR PHOTONIC INTEGRATION: DESIGN AND PROCESS

LEE CHEE WEI

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
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Abstract

Photonic integration is the integration of several photonic devices on one common material platform to form an integrated circuit. In this thesis, some building blocks required for photonic integration are designed and demonstrated. They are designed to address three important issues faced by integration, i.e, the coupling loss due to size mismatch between standard optical fiber and the devices on the chip, the polarization dependence of the devices, and the monolithic integration of both active and passive devices. The fabrication processes of photonic devices are also studied and are used in the fabrication of simple photonic integrated device.

The applications of asymmetric waveguides vertical coupler in photonic integrated circuits are studied in this thesis. We present a coherent approach to the design of compact vertical coupler with variable polarization dependence. As a polarization-independent coupler the vertical coupler is shown to transfer light with more than 90% efficiency for both Transverse Electric (TE) and Transverse Magnetic (TM) polarizations. As a polarization mode splitter, the vertical coupler is shown to preferentially couple TE or TM polarizations with a contrast ratio of up to 19 dB. This versatility makes the vertical coupler a compact and useful input-stage device that not only maximizes input/output coupling efficiency to small devices, but also provides a degree of polarization control before the device.

In PIC, many devices have to be single-mode for proper operation, while the input and output waveguides may be multimode to minimize coupling loss with fibers. The transition from multimode to single-mode waveguides can be achieved by using a mode filter. The design of mode filter for ridge high index contrast waveguide using laterally tapered waveguide is proposed and presented in this thesis. The mode filter is found to be insensitive to many of the device's dimension. In the thesis, a polarization-independent coarse wavelength splitter based on a single ridge-type

lateral directional coupler is also proposed. This polarization-independent wavelength splitting is achieved by exploiting the polarization dependence of the waveguides to produce coupling lengths that are sensitive to polarization and wavelength.

Beside the design work, the fabrication processes of photonic devices are studied in the thesis, with emphasis on developing a room-temperature dry-etching process for InP using chlorine gas, which is a key process for forming ridge waveguides. The etch rate achieved is comparatively high (~ 800 nm/min) and the sidewall is almost 90° . The root-mean-square surface roughness is also less than 5 nm. Ridge waveguides are fabricated and the propagation loss achieved is not the best reported so far probably due to the rough sidewall, but nonetheless it shows that a room-temperature chlorine etching process is possible.

After the fabrication processes are studied, they are used to fabricate simple photonic integrated devices. As an initial demonstration, we have fabricated an integrated device involving the vertical coupler and the multimode interferometer (MMI). The results obtained from the measurement shows that the device is able to perform as desired, even though the loss and transfer efficiency is lower than expected from the simulations. We have also fabricated a 1×2 passive MMI integrated with two active electroabsorption (EA) switches. The device could be used as a switch for network signal distribution. The integrated device is found to give poor extinction ratio, which is about 10.5 dB only, probably because the material and the waveguide structures are not optimized for the electroabsorption effect, and also the fabrication process requires further modifications. The active and passive devices are integrated monolithically on an InP chip by quantum well intermixing (QWI). Two QWI methods, i.e., the argon plasma-enhanced intermixing and the impurity-free vacancy disordering, are studied and compared. The latter is more repeatable and gives a sufficiently large bandgap differential blueshift, which is about 100 nm. Hence, it is used in the device fabrication process.

Table of Contents

Acknowledgement	i
Abstract	iii
Table of Contents	v
List of Figures and Tables	viii
List of Abbreviations	xx
Chapter 1 Introduction	1
1.1 Motivation	1
1.1.1 Technology and Device Building Blocks	3
1.1.2 Process Development and Device Fabrication	8
1.2 Objectives	9
1.3 Major Contributions	10
1.4 Report Organization	12
Chapter 2 Background Information and Literature Survey	13
2.1 Photonic Integration	14
2.2 Photonic Waveguides	16
2.3 Vertical Couplers	18
2.4 Lateral Mode Filters	24
2.5 Wavelength Splitters	26
2.6 Photonic Waveguide Fabrication Process	28
2.6.1 General Fabrication Process	28
2.6.2 Dry Etching of Waveguides	30
2.6.3 Quantum Well Intermixing	33
2.7 Electroabsorption Modulator	36
Chapter 3 Design of Vertical Couplers for Polarization Independent Coupling and Polarization Splitting	39
3.1 Principle of Vertical Coupling	40
3.2 Design of Polarization-independent Vertical Coupler	42
3.2.1 Design Structure and Principle	42
3.2.2 Design of Underlying Waveguide	46
3.2.3 Design of Tapered Top Waveguide	48
3.2.4 Examples of Polarization-independent Vertical Coupler Design	50

Table of Contents

3.3	Design of Polarization Splitters	53
3.3.1	Design Principle	53
3.3.2	Example of Polarization Splitter Design	55
3.4	Other Applications and Considerations	57
3.4.1	Fabrication Tolerance	57
3.4.2	Multimode Characteristic	62
3.4.3	Gaussian Mode Input	63
3.4.4	Three-Layer Vertical Coupler	64
3.5	Design of Single-Mesa Vertical Coupler	66
	Chapter Summary	73
Chapter 4	Design of Lateral Mode Filter	75
4.1	Design Structure and Principle	76
4.1.1	Waveguide Mode in High-Index-Contrast (HIC) Waveguide	76
4.1.2	Application of Mode Filter	77
4.1.3	Design Structure and Principle of Higher Order Mode Filtering	78
4.2	Example of Design and Discussions	80
	Chapter Summary	87
Chapter 5	Design of Polarization-Independent Coarse Wavelength Splitters based on Ridge Waveguide Conventional Directional Coupler	88
5.1	Design Principle	89
5.2	Structural Dependence	92
5.3	Design Examples	94
5.4	Performance and Sensitivity	96
5.4.1	Figure of Merit	96
5.4.2	Sensitivity	99
	Chapter Summary	100
Chapter 6	Optimization of Room Temperature Inductively Coupled Plasma (ICP) Dry-etching of InP	102
6.1	Experiment	103
6.1.1	Plasma-enhanced Chemical Vapor Deposition (PECVD) Process	103
6.1.2	Reactive Ion Etching (RIE) of SiO ₂	104

Table of Contents

6.2 Optimization of Room Temperature InP Etching	106
6.2.1 Methane/hydrogen (CH ₄ /H ₂) Process	106
6.2.2 Chlorine/methane/hydrogen (Cl ₂ /CH ₄ /H ₂) Process	110
6.2.3 Chlorine/Nitrogen (Cl ₂ /N ₂) Process	115
6.3 Device Measurement	117
6.3.1 Uniform High-Index-Contrast Waveguide	117
6.3.2 Multimode Interferometer (MMI)	120
Chapter Summary	122
Chapter 7 Quantum Well Intermixing (QWI) for Integration of Passive and Active Devices	124
7.1 Intermixing Mechanism	125
7.2 Experiment	127
7.3 Results and Discussions	128
7.4 Measurement of Intermixed Waveguides	135
Chapter Summary	136
Chapter 8 Demonstration of Photonic Integrated Devices	138
8.1 Integration of Single-Mesa Vertical Coupler and Multimode Interferometer	139
8.1.1 Design of Multimode Interferometer and Single-Mesa Vertical Coupler	139
8.1.2 Fabrication Results and Discussions	144
8.2 Integration of Multimode Interferometer and Electroabsorption Modulators	148
8.2.1 Fabrication of Integrated MMI and EA Switches	148
8.2.2 Results and Discussions	156
Chapter Summary	159
Chapter 9 Conclusions and Recommendations	160
Author's Publication	165
References	168

List of Figures and Tables

Figures:

Fig. 1.1	Illustration of the selective-area (a) etch, and (b) regrowth process	4
Fig. 1.2	Schematic of ridge high index contrast waveguide	6
Fig. 2.1	2-D illustration for total internal reflection of an optical waveguide, showing how the light is confined in the waveguide core, which is represented by region 1. Region 2 is denoted as the waveguide cladding. n —refractive index	16
Fig. 2.2	Schematic of a (a) ridge waveguide, and (b) rib waveguide, and their corresponding simulated fundamental mode profiles	17
Fig. 2.3	Illustration of light coupling from a semiconductor laser to a standard single mode fiber through a vertical spot-size-converter	18
Fig. 2.4	Examples of vertical coupler with vertical taper and lateral taper in the ridge and the buried waveguide structures	20
Fig. 2.5	Schematic of wavelength filter utilizing the cross waveguides vertical coupler [54]. λ -wavelength	21
Fig. 2.6	Schematic (top view) of polarization splitter using (a) Mach-Zehnder interferometer [62], and (b) mode selective channel waveguide [65]. P—polarization	23
Fig. 2.7	Schematic of polymer vertical branching polarization splitter [66]	23
Fig. 2.8	Illustration of polarization-diversity detection employing the vertical coupler polarization splitter. P—polarization	24

Fig. 2.9	(a) Side view of the vertical Y junction waveguides mode filter [72], and (b) top view of a MMI mode filter [69] that show the mode field profiles of the propagating wave at different location of the devices	26
Fig. 2.10	Process flow for fabricating a semiconductor ridge waveguide	29
Fig. 2.11	Photographs taken by Scanning Electron Microscope (SEM) on the etched profiles from (a) wet etching, and (b) dry etching	31
Fig. 2.12	Effect of QWI on the bandgap profile and the photon absorption behavior of a blueshifted material	34
Fig. 2.13	(a) Simulated absorption spectra for a single quantum well under different electric field, F , and (b) the band diagram illustrating the effect of electric field [109]. E_{h1} —first hole energy level; E_{e1} —first electron energy level	38
Fig. 3.1	A general waveguide coupler with two waves, E_1 and E_2 propagating in the waveguides having propagation constants β_1 and β_2 , respectively. $\Delta\epsilon$ represents the perturbation in the permittivity of the waveguide materials	40
Fig. 3.2	Schematic of vertical coupler attached to a photonic device.	43
Fig. 3.3	Effective index of the individual waveguide at various taper widths for TE and TM polarizations	44
Fig. 3.4	(a) Critical widths, and (b) the corresponding effective indexes at the critical widths for the different combinations of core thickness and refractive index for the top waveguide core. The color bands represent the different ranges	46
Fig. 3.5	Effective indexes of the various refractive indexes for the underlying waveguide core with cross section of $4 \times 3 \mu\text{m}^2$	48

Fig. 3.6	Sketches of the effective index profiles along the longitudinal direction of the vertical coupler for both TE and TM polarizations. The various regions and design parameters are identified	50
Fig. 3.7	Effective index of the individual waveguide at various taper widths for the case of (a) passive top waveguide, and (b) active top waveguide. n —refractive index	51
Fig. 3.8	Simulated power distribution between the top and underlying waveguides for the design with (a) passive actual device, and (b) active actual device, along with their mode contour plots (c) and (d), respectively	52
Fig. 3.9	Transverse field profiles for the vertical coupler showing the mode size at various propagation (longitudinal) distances: (a) $Z=0\text{ }\mu\text{m}$, (b) $Z=50\text{ }\mu\text{m}$, (c) $Z=100\text{ }\mu\text{m}$, (d) $Z=150\text{ }\mu\text{m}$, (e) $Z=200\text{ }\mu\text{m}$, and (f) $Z=250\text{ }\mu\text{m}$, demonstrating the spot-size conversion capability of the vertical coupler	53
Fig. 3.10	Effective indexes as a function of the taper widths for the confined TE and TM supermodes (solid curves) of the vertical coupler and the individual uncoupled waveguides (dotted curves)	55
Fig. 3.11	(a) Transfer efficiencies to the top waveguide for the TM-preferred vertical coupler and TE-preferred vertical coupler, with their contour plots in (b) and (c), respectively	56
Fig. 3.12	Transfer efficiency to the top waveguide for various spacer thicknesses	58
Fig. 3.13	Transfer efficiencies for deviation in (a) initial width, and (b) final width from their original values of $1.40\text{ }\mu\text{m}$ and $2.00\text{ }\mu\text{m}$, respectively	58

Fig. 3.14	Transfer efficiency to top waveguide for various transfer/taper lengths, with the initial width and final width remain unchanged at 1.40 μm and 2.00 μm , respectively	59
Fig. 3.15	Transfer efficiencies as a function of deviations in the upper waveguide core index for various taper velocities or taper differential widths	61
Fig. 3.16	Transfer efficiency against different deviations of operating wavelength. The optimum operating wavelength is assumed to be 1.55 μm	61
Fig. 3.17	Simulated transfer efficiencies for the different mode order of the underlying waveguide, for both TE and TM polarizations. For illustration, the insets show the corresponding mode intensity profiles for TE polarization	63
Fig. 3.18	Power distribution along the propagation distance for a standard SMF mode input (Gaussian approximation) with TE polarization	64
Fig. 3.19	Relative power distribution along the propagation distance for TE mode. TM mode is similar. The inset shows the schematic of the cross section for the three-level vertical coupler. WG—waveguide	65
Fig. 3.20	Comparison between the conventional double-mesa vertical coupler process and the single-mesa vertical coupler process	67
Fig. 3.21	Schematic of single-mesa vertical coupler	68
Fig. 3.22	Simulated fiber coupling loss to the single-mesa vertical coupler for: (a) various bottom core thicknesses at different spacer thickness, (b) different spacer thickness at the optimum bottom core thickness, and (c) different top waveguide width at different spacer thickness	69

Fig. 3.23	Effective index curves of the single-mesa vertical coupler. The top waveguide core has a refractive index of 3.50, while the bottom waveguide has a refractive index of 3.42	71
Fig. 3.24	Transfer efficiency of the single-mesa vertical coupler for various final taper widths at the transfer lengths of 150 μm and 400 μm	72
Fig. 3.25	(a) Contour plot showing the light transfer, and (b) transfer efficiency, to the top waveguide, for TE and TM polarizations along the propagation distance	73
Fig. 4.1	Effective index of a representative InP-based HIC waveguide at different widths for TE and TM polarizations. Insets show the mode intensity profiles and the waveguide cross section	77
Fig. 4.2	Normalized waveguide powers along the propagation distance for the directional coupler when the input is the fundamental mode and first order mode	78
Fig. 4.3	Schematic of the higher order guided modes filter (not drawn to scale)	79
Fig. 4.4	Transverse intensity profiles of the multimode HIC input waveguide, with the different colors represent the intensity distribution	81
Fig. 4.5	Simulated lateral intensity profiles (X-Z) along the propagation distance when the input mode is (a) $v=0$ (fundamental mode), (b) $v=1$, (c) $v=2$, (d) $v=3$ (the monitor height is 1.75 μm from the top of the ridge, which coincides with the middle of the core layer), and (e) the vertical contour plot for $v=2$ in the Y-Z plane at the center of the waveguide, showing the substrate leakage loss that occurs mostly in the input taper and the single-mode waveguide. The ridge is 2 μm deep	82

Fig. 4.6	Calculated losses for the fundamental and first-order modes (both TE and TM) at the end of the output taper, for various single-mode waveguide widths, with an etch depth, D_{etch} of 2 μm (solid curves) and 4 μm (dotted curves). The simulated device consists of 30 μm input and output taper sections and a 30 μm single-mode waveguide section	83
Fig. 4.7	Calculated losses for the first order mode (both TE and TM) at the output of the filter as a function of the single-mode waveguide length. The width of the waveguide is assumed to be 0.8 μm . The etch depth is 2 μm and the input taper length is 5 μm and 30 μm , respectively. The output taper length is fixed at 30 μm	85
Fig. 4.8	Calculated total losses for the fundamental TE and TM modes as a function of input taper length (solid curves), with the output taper length fixed at 30 μm ; and as a function of output taper length (dotted curves), with the input taper length fixed at 30 μm . The single-mode waveguide width is 0.8 μm and the length is 30 μm	86
Fig. 5.1	Amplitude profiles of the normal modes for the two waveguides in a conventional directional coupler	90
Fig. 5.2	Illustration of input with (a) different wavelengths exiting at different ports (wavelength splitting), and (b) different polarizations for a single wavelength exiting at the same port	91
Fig. 5.3	InP-based directional couplers: (a) Effective indices for even and odd modes, and (b) coupling lengths, for both TE and TM as a function of gap size g , with $w=0.4 \mu\text{m}$. Inset shows the schematic of the directional coupler	93
Fig. 5.4	Simulated power in the bar waveguide for TE and TM polarizations of (a) $\lambda=1.31 \mu\text{m}$, (b) $\lambda=1.54 \mu\text{m}$, and (c) the corresponding field profiles along the directional coupler	94

Fig. 5.5	The crosstalk as a function of wavelength in μm at (a) the cross port ($\lambda_c=1.31 \mu\text{m}$), and (b) the bar port ($\lambda_b=1.54 \mu\text{m}$)	99
Fig. 5.6	TE and TM crosstalks at the bar port and the cross port of the CWDM directional coupler for various (a) waveguide widths, and (b) gap sizes in μm	100
Fig. 6.1	Deposited thickness of SiO_2 by PECVD over time, with inset showing the deposition parameters. The gas flow rates are measured in standard cubic centimeters per minute (sccm)	104
Fig. 6.2	Etch depth of SiO_2 and AZ-5214e photoresist against etching time for the optimized recipe using RIE	105
Fig. 6.3	Schematic of the ICP machine used in the optimization of room temperature InP etching	106
Fig. 6.4	Taguchi linear graphs showing the mean etch rate for different (a) RF power, (b) ICP power, (c) process pressure, and (d) $\text{CH}_4:\text{H}_2$ flow rate, levels	108
Fig. 6.5	SEM of the waveguide structure when the process pressure is increased from (a) 18mTorr, to (b) 25mTorr, and (c) 32mTorr. The RF power is 100W, ICP power is 400W, and $\text{CH}_4:\text{H}_2:\text{O}_2=30:10:1$ sccm	109
Fig. 6.6	(a) SEM of the InP mesa structure under the optimized $\text{CH}_4:\text{H}_2$ recipe, and (b) 3-D Atomic Force Microscopy (AFM) profile of the material surface. The RF power is 300W, ICP power is 100W, process pressure is 20 mTorr and $\text{CH}_4:\text{H}_2:\text{O}_2=40:30:1$ sccm	110
Fig. 6.7	Taguchi linear graphs showing the mean etch rate as a function of (a) RF power, (b) ICP power, (c) Cl_2 flow rate, (d) CH_4 flow rate, (e) H_2 flow rate, and (f) process pressure	112

List of Figures & Tables

Fig. 6.8	InP etch rates for different ICP powers, with RF power set at 100W, process pressure set at 4 mTorr, Cl ₂ , CH ₄ and H ₂ flow rates set as 10, 8 and 4 sccm, respectively	113
Fig. 6.9	(a) SEM of the InP mesa structure under the optimized Cl ₂ :CH ₄ :H ₂ recipe, and (b) 3-D AFM profile of the material surface. The RF power is 100W, ICP power is 1200W, process pressure is 4 mTorr and Cl ₂ :CH ₄ :H ₂ =10:8:4 sccm	114
Fig. 6.10	InP etch depth at different etch time, with RF power set at 100W, ICP power set at 1200W, process pressure set at 4 mTorr, Cl ₂ , CH ₄ and H ₂ flow rates set as 10, 8 and 4 sccm, respectively	115
Fig. 6.11	SEM photos of the mesa structure etched using the Cl ₂ /N ₂ optimized recipe, with (a) showing the cross section profile, and (b) the corresponding 3-D AFM surface profile. The RF power is 125W, ICP power is 700W, process pressure is 4 mTorr, Cl ₂ flow rate is 10 sccm and N ₂ flow rate is 5 sccm	116
Fig. 6.12	Photoluminescence result of the wafer with waveguide structure. The measurement is done under room temperature ambient	118
Fig. 6.13	(a) Output modes of a 5 μm and an 8 μm waveguides, and (b) FP fringes obtained from the 8 μm waveguide measurement, with insets showing the mode profiles at the maxima and minima wavelength	119
Fig. 6.14	SEM of the fabricated 1×2 MMI, showing (a) the input region, (b) the output region, and (c) the output mode as observed by the infrared camera	121
Fig. 7.1	Blueshift induced by the two QWI techniques, i.e., the PE-QWI and the IFVD techniques on the (a) 3 quantum wells, and (b) 6 quantum wells structures. The as-grown samples are annealed alongside	129

Fig. 7.2	Bandgap blueshift for the different argon plasma exposure times. The samples are annealed subsequently at the 650 °C for 120s	130
Fig. 7.3	Blueshift generated by the IFVD with SiO ₂ cap layer and the RTA only samples for different annealing time. The annealing temperature is set at 750 °C	132
Fig. 7.4	Blueshift of the actual samples for the different annealing temperature, with the annealing time set at 120s	133
Fig. 7.5	Blueshift of the actual samples for the different anneal time, with the anneal temperature set at 700 °C	134
Fig. 7.6	PL spectrum of the 3 quantum wells waveguide sample after the IFVD QWI with RTA at 700 °C for 120s. The PL is done at 77K ambient	135
Fig. 7.7	Output mode profiles of the waveguides, with (a), (b) from the intermixed region, and (c), (d) from the non-intermixed region	136
Fig. 8.1	PL spectrum of the epitaxy wafer with the SMVC layer structure. The PL is done at 77K to reduce the background noise	140
Fig. 8.2	Schematic of the 1×2 MMI, showing the various dimension of the MMI and the location of the ports. The SMVC is assumed to be attached to the input port	141
Fig. 8.3	Simulation results for the 1×2 MMI for TE and TM polarizations. The intensity contours are taken at the centre of the top waveguide core, 1.8 μm from the top of the structure	142
Fig. 8.4	Simulation results of the integrated device of SMVC and 1×2 MMI for TE and TM polarizations. The contour plots are obtained at a horizontal plane parallel to the centre of the top waveguide core	143

Fig. 8.5	Transfer efficiency of the SMVC for different final taper widths for TE and TM polarizations	144
Fig. 8.6	SEM photographs showing (a) the 1×2 MMI, (b) the output waveguides of the MMI after the S-bend to ensure some separation (~50 μm) between the two waveguide modes on the infrared camera, and (c) part of the taper waveguide. There is some dirt observable in (a) since the SEM system is not located in the cleanroom	145
Fig. 8.7	Measured output mode profiles from (a) underlying rib waveguide, (b) single-mesa vertical coupler, and (c) integrated device of SMVC and 1×2 MMI	146
Fig. 8.8	Process flow of the MMI and EAM integrated device	149
Fig. 8.9	SEMs showing (a) the isolation trench that separates the active and passive regions, and (b) cross sectional view of the trench	150
Fig. 8.10	SEM of the mesa structure for MMI waveguide, covered with a layer of conformal SiO ₂ passivation layer deposited by PECVD	151
Fig. 8.11	Top view of the electrical P-contact of the device before the metal deposition	152
Fig. 8.12	Illustration of process flows for lift-off technique using (a) positive photoresist, and (b) AZ-5214e with image reversal method, which produces the undercut profile beneficial for lift-off process	153
Fig. 8.13	(a) SEM of the P-electrodes. The electrodes are deposited directly on top of the EAM waveguides, where the InGaAs layer is exposed, as shown in (b) the cross-sectional view of the active waveguide. The square contact pads in (a) are created for easier probing during the measurement stage. Other areas are still covered with passivation SiO ₂	154

List of Figures & Tables

Fig. 8.14	SEM of two of the alignment markers	155
Fig. 8.15	SEM of the completed integrated devices of MMI and EAM	156
Fig. 8.16	Photocurrent (absorption) spectra of the fabricated MQW EA switch as a function of input optical wavelength with external reverse bias voltages of 0-5 V	157
Fig. 8.17	Extinction ratio of the MMI and EAM integrated device as a function of external reverse bias voltage and polarization, at the operating wavelength of 1530 nm, with the insets showing the optical modes obtained at different voltages	158
Fig. 8.18	Waveguide profile measured directly from the 8 μm MMI input port	159

Tables:

Table 2.1	Thermal expansion coefficient of various dielectrics and III-V compound semiconductors at 300K. The ternary InGaAs and quaternary InGaAsP presented are lattice-matched to InP [106-108]	35
Table 3.1	Design parameters for the 3-layer vertical coupler	66
Table 5.1	Refractive index of $\text{Si}_{0.9}\text{Ge}_{0.1}$ and Si materials for TE and TM modes of $\lambda=1.31\text{ }\mu\text{m}$ and $1.55\text{ }\mu\text{m}$	95
Table 6.1	Different levels assigned to the process parameters for the CH_4/H_2 process optimization	107
Table 6.2	Different levels assigned to the process parameters for the $\text{Cl}_2/\text{CH}_4/\text{H}_2$ process optimization	111
Table 6.3	Layer structure of the waveguide	118
Table 6.4	Summary of the optimized room temperature InP etching recipes	122
Table 7.1	Layer structure of the epitaxy wafers used in the QWI experiments. The difference between the two wafers lies in the number of quantum wells, q. QW—quantum well, QWB—quantum well barrier	127
Table 7.2	Layer structure of the epitaxy wafers used in the actual integrated device fabrication	133
Table 8.1	Layer structure for the SMVC and MMI integrated device	140

List of Abbreviations

AFM	Atomic Force Microscopy
BCB	Benzocyclobutene
BPM	Beam Propagation Method
CWDM	Coarse Wavelength Division Multiplexing
DC	Directional Coupler
DWDM	Dense Wavelength Division Multiplexing
EA	Electroabsorption
EAM	Electroabsorption Modulator
ECR	Electron Cyclotron Resonance
EO	Electrooptics
FDBPM	Finite Difference Beam Propagation Method
FDTD	Finite-difference Time-domain
FP	Fabry-perot
FTTH	Fiber-to-the-home
HIC	High Index Contrast
ICP	Inductively Coupled Plasma
IFVD	Impurity-free Vacancy Disordering
IMRE	Institute of Material Research Singapore
MBE	Molecular Beam Epitaxy
MMI	Multimode Interferometer

List of Abbreviations

MOCVD	Metal-organic Chemical Vapor Deposition
MQW	Multiple Quantum Well
MZI	Mach-Zehnder Interferometer
NTU	Nanyang Technological University
OMT	Optical Mode Transformer
PDL	Polarization Dependent Loss
PECVD	Plasma-enhanced Chemical Vapor Deposition
PE-QWI	Plasma-enhanced Quantum Well Intermixing
PIC	Photonic Integrated Circuits
PL	Photoluminescence
PON	Passive Optical Network
QCSE	Quantum-confined Stark Effect
QW	Quantum Well
QWB	Quantum Well Barrier
QWI	Quantum Well Intermixing
RF	Radio Frequency
RIE	Reactive Ion Etching
RMS	Root-mean-square
RTA	Rapid Thermal Anneal
RTP	Rapid Thermal Processing
SEM	Scanning Electron Microscope
SMF	Single-mode Fiber

List of Abbreviations

SMVC	Single-mesa Vertical Coupler
SOA	Semiconductor Optical Amplifier
SOI	Silicon-on-insulator
SSC	Spot-size-converter
TE	Transverse Electric
TIR	Total Internal Reflection
TM	Transverse Magnetic
UV	Ultraviolet
VC	Vertical Coupler
WDM	Wavelength Division Multiplexing

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Introduction

1.1 Motivation

Photonic integration involves integration of several photonic devices on one common platform. Integration is a natural evolution from discrete components. Discrete integration is the integration of different discrete devices, all connected by optical fiber, to achieve a desired functionality. The systems are usually bulky and consume higher costs. Hybrid integration refers to the integration of multiple devices of different material systems on one common substrate. One such example would be the integration of a III-V semiconductor laser with a silicon passive waveguides network. The size of the system is much smaller, but the compatibility between the devices made of different materials could be a problem. Hybrid integration could involve flip-chip bonding of one device on another, or the wafer bonding or epitaxy growth of one material on another. Finally, monolithic integration integrates devices on a single substrate, all of the same material system. It gives the lowest system cost and the smallest achievable device area. It also reduces the compatibility issue, as the devices are all from the same material system. However, not all devices can be fabricated in the same material, and even devices that may have different requirements that are difficult to meet, hence monolithic integration is also limited in functionality and quite a challenge to realize.

The concept of Photonic Integrated Circuit (PIC), a photonic chip with many devices and multifunctional capability, actually emerged in the 1960s, about the same period where integrated electronics started moving to the forefront of technology. However, advances in PIC are few and limited compared to its electronic counterpart. This is because a functional PIC usually requires many different devices, both active and passive, each of which may have a distinct functionality and requirement. In contrast, complicated electronic IC can be formed just by transistors and a few passive components.

The rapid development in optical communication systems has accelerated the drive for more integrated photonic devices because of the advantages it can provide. PIC is able to reduce the system size and cost, and improve the reliability as the number of discrete devices is reduced. Besides, it minimizes the number of fiber interconnections between the discrete devices, which is usually the main source of optical loss, especially if the photonic devices are small compared to the fiber. Also, since the devices are now very near to each other on the same substrate, the optical propagation loss could be reduced as well.

Despite the advantages that PIC can provide, the search for a universal platform is still an elusive goal. Monolithic integration is the preferred architecture of integration. Since multiple optical devices are to be integrated into a chip with minimum size and maximum functionality, the devices must be compatible with each other and the integration platform must be able to support the different devices. Generally, the material used for monolithic integration must possess the following characteristics.

- It must support all passive (light guiding) and active optical functions (modulation, amplification, switching and etc.) required for a particular circuit.
  - It must be able to provide material bandgap in telecommunication wavelengths (the 1.30-1.60 μm wavelength window)
  - It must demonstrate good electrical functionality for optoelectronic applications, and
  - It must be suited for miniaturization.
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One of the most commonly used materials that fulfill all the above requirements is the compound semiconductor Indium Phosphide (InP). Therefore, it will be used throughout our study. Although Silicon photonics has been greatly pursued as a cheaper solution and having more mature fabrication technologies, the effort is mainly focused on passive devices and hybrid integration, as the silicon laser source is unavailable due to its indirect material bandgap. Even though optically pumped laser source has been proposed [1-6], but an electrically-pumped laser source is still unavailable but preferred.

The scope of this thesis includes two parts. The focus for the first part is on design of device building blocks, while the second part is directed to process development and device fabrication, including simple integrated circuits and their measurements.

1.1.1 Technology and Device Building Blocks

In monolithic integration, several approaches to create regions with different material bandgaps on the same substrate have been presented in literature. The different material bandgaps are needed because the active and passive devices require bandgap that is absorbing and non-absorbing at the operating wavelength, respectively. One of such approaches is the etch-and-regrowth process as illustrated in Fig. 1.1. However, this method tends to sacrifice simplicity and yield, and exacerbate the scattering and reflection losses at the growth interfaces. Quantum Well Intermixing (QWI) [7-11] is a relatively simple alternative which involves post-growth manipulation of the bandgap of a quantum well, and it allows the active and passive devices to co-exist on the same material layer without regrowth.

Fig. 1.1. Illustration of the selective-area (a) etch, and (b) regrowth process.

All the above-mentioned approaches are limited to lateral integration, and require both the active and passive devices to share the same layer thicknesses and doping, which is not always desired. Active devices usually require smaller thickness for the light confinement layer and higher doping at the contact layer, such as those in lasers diode or in modulators. For passive devices like waveguides, such requirement is not necessary. In fact, larger waveguides have less propagation loss, lower fiber coupling loss and are easier to fabricate. Lower doping also reduces the free carrier loss.

Some of the problems discussed above can be relieved by using vertical integration, in addition to planar integration. Vertical integration integrates devices vertically, and the devices on different vertical levels communicate through the vertical coupling of light. Hence, a vertical coupler (VC), which comprises two vertically stacked waveguides capable of coupling light between each other, is essential as it provides the way to facilitate vertical integration. Because the devices and waveguides are constructed on different lateral planes, they are able to provide several useful advantages and solutions to the problem discussed previously, and these are summarized below.

- The devices can have different layer thicknesses. For example, one can have a thicker and wider waveguide that serves as the input to an active device, which is very thin and narrow. The larger waveguide can improve the fiber coupling because it increases the modal overlap with the optical fiber.

- It allows the flexibility in having different material bandgaps, doping concentrations, or refractive indexes in different layers, such as higher refractive index for the active devices, and lower refractive index for passive waveguides. This can be done in just a single epitaxy growth.
- It provides another dimension of photonic integration, which is the vertical integration. Together with other planar integration techniques, they can lead to a 3-D high-density PIC.

Due to these advantages, it is worthwhile to study and explore the possible applications of vertical coupler in photonic integrated circuits.

In real photonic systems, the polarization of the optical signal propagating in an optical fiber is unknown. If the performance of the vertical coupler is polarization dependent, it may transfer one polarization effectively but not the other, thereby causing high polarization-dependent loss. Thus, polarization independence is an important requirement for the vertical coupler, and in fact for many other devices.. Therefore, in the thesis, a polarization-independent vertical coupler is designed to solve the problem. On the other hand, there might be some situations in which only one polarization is needed, for example in polarization-diversity detection. In such case, a polarization splitter (or filter) is required. In the thesis, we have proposed that a polarization splitter can be designed from the vertical coupler. This has extended the application of the vertical coupler, where it not only improves the fiber coupling to small devices, but it could also provide a polarization control mechanism for devices that need it.

Both of the applications are designed based on some unique characteristics of ridge-structure vertical coupler that have not been utilized in any literature. Fig. 1.2 shows a typical cross section of the ridge waveguide that is used in our device designs. The uniqueness of ridge waveguide from others is the availability of the lateral air-core interfaces. If the core has a much higher material index as compared to air, then the ridge waveguide can also be denoted as high index contrast (HIC) waveguide. In the

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InP-based waveguide, the core is usually an epitaxy layer of quaternary semiconductor, i.e., Indium Gallium Arsenide Phosphide (InGaAsP), grown on an InP substrate by metal-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) technologies. By changing the composition of the elements, different material refractive indexes could be obtained.

Fig. 1.2. Schematic of ridge high index contrast waveguide

In photonic integration, the high index contrast waveguides have been widely used in device interconnects and in constructing compact photonic devices. This is due to the strong lateral confinement of the waveguide which allows sharp bends and narrower waveguides. These will certainly contribute to minimizing overall device area. Despite these advantages, one challenge in the use of HIC waveguide is the difficulty in constructing a single-mode waveguide, which is required by many photonic devices such as the directional coupler and Mach-Zehnder interferometer (MZI). In a directional coupler, for example, different modes have different coupling lengths; hence a mixture of modes at the input will reduce the coupling efficiency and increase the crosstalk.

A mode is a solution of the Maxwell equations in the waveguide. Each waveguide mode has a distinct propagation constant, with the fundamental mode having the highest amongst all. Vertically, a HIC waveguide can be single-mode by having a small cladding-core index difference, but laterally it is generally multimode due to the high index contrast interface. To be laterally single-mode, a high index contrast waveguide would need to have a very narrow width ($<1\ \mu\text{m}$), which could incur other problems—

high propagation loss over long distances and high input fiber coupling loss. Hence, sometimes for a long single-mode device like MZI, wider waveguides are still used to minimize propagation loss even though they are not single-mode. In smaller single-mode devices like microresonators, the single-mode bus waveguide is often tapered up to a wider multimode waveguide for low-loss interconnection outside the device [12]. Nevertheless, in a multimode waveguide, higher-order modes exist and, if not suppressed, can affect the performance of the single-mode device. In such cases, a lateral mode filter strategically placed at the input to filter out higher-order modes is critical to ensure single-mode operation and performance.

In this thesis, a simple mode filter constructed using an extension of the laterally taper waveguides in a back-to-back architecture is proposed. This architecture is compact, easily integrated into existing device design, and in our simulation, it is effective in filtering out all higher-order modes while passing only the fundamental mode (both TE and TM polarizations) with minimal insertion loss. The concept is simply to filter out higher order modes in a multimode waveguide by interposing a single-mode section, while using taper transitions to minimize reflection and interference effects and the re-excitation of the filtered modes. Although a similar approach has been presented before for silicon material [13], the novelty of our design is that the mode filter is much more compact, and has lower fundamental mode loss and higher filtering efficiency.

Aside from polarization-splitting and mode filtering, wavelength splitting (demultiplexing) and combining (multiplexing) are important functions in many optical applications. An important example is fiber-to-the-home (FTTH) application, in which the 1.3 μm and 1.5 μm wavelength regions may be used to carry data/voice and video, respectively [14]. Since the wavelengths are spaced far apart, a coarse WDM (CWDM) filter would be needed to separate or combine the wavelengths. A bidirectional and compact filter that can be integrated with transceivers is desirable, as it would facilitate the development of low-cost terminal units for the home. Therefore, the filter should ideally be based on integrated optics, be polarization independent, and have large

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optical bandwidth and low crosstalk. An integrated optic realization of the ubiquitous fused fiber coupler is the waveguide directional coupler (DC). In this thesis, we show theoretically that compact and polarization-independent dual-wavelength splitters based on a single lateral directional coupler are possible. The design is also based on strongly confined, high-index contrast ridge waveguides, as opposed to the conventional weakly-guided, low-index contrast, rib or buried waveguides used in most other designs.

1.1.2 Process Development and Device Fabrication

In the fabrication of generic photonic devices, processes such as lithography, etching, material deposition and annealing have been adopted from the silicon microelectronic IC. In the etching of the material, dry-etching is preferred to wet-etching, as it ensures that the desired patterns are transferred precisely onto the substrate. This is possible due to the anisotropic nature of dry etching, in contrast with the isotropic reaction that occurs in wet etching. Dry etch employs both chemical and physical actions between the reactive gas species and the etched material to achieve good directionality and speed. One advanced form of dry etch designed for high etch rate and directionality (i.e., giving smooth vertical sidewalls) is known as inductively coupled plasma (ICP) reactive-ion etch (RIE). In Nanyang Technological University (NTU), we have an ICP system by Oxford Instrument (U.K.). The system is ideal for etching GaAs and InP-based materials using a Chlorine-based process. GaAs can be etched at room temperature while the etching of InP is usually done at elevated temperature ($>200^{\circ}\text{C}$) with the use of heated stage and temperature controller. Unfortunately, our system does not have a heated stage and it is costly to upgrade. Thus, under this situation we were forced to develop a room- temperature dry etch process for InP materials. We developed such a process using a combination of gases that works almost as well as the standard high-temperature process (in terms of etch

rate, verticality, and sidewall smoothness) but with much shorter cycle time. This work is summarized in Chapter 6.

After the design and process development of the photonic devices, it is important to demonstrate the integration of multiple photonic devices. This represents the final goal of the project. Simple integration of two photonic devices will be demonstrated. This includes:

- Integration of multimode interferometer (MMI) and electroabsorption modulator (EAM), and
- Integration of vertical coupler and multimode interferometer

These simple integrated devices carry specific functions which will be explained in the corresponding chapters.

With all the above-mentioned motivations, the reasons for carrying out studies as described in this thesis are justified.

1.2 Objectives

Photonic integration is a rather broad area, and it involves many building blocks, architectures and material platforms. Thus, in this project, we will only focus on several devices, namely the vertical coupler, mode filter, directional coupler, multimode interferometer and electroabsorption modulator. The platform material of interest will be the InP-based compound semiconductor. Besides, we will study on the fabrication process of the devices, with the main focus on dry-etching, in order to realize some of the devices and their integration. In essence, this research project aimed to:

- Design and explore the possible application of vertical coupler in photonics integration
- Design and explore the possible PIC building block that could be used for mode filtering in photonic integrated circuits

- Design and explore the possible PIC building block that could be used as a wavelength splitter in polarization-independent fashion
- Study and improve the dry-etching process utilizing inductively coupled plasma RIE, and
- Integrate photonic devices monolithically to develop a simple PIC subsystem (less than three devices).

1.3 Major Contribution

The design of vertical coupler and mode filter are the major achievements in the design part of my thesis. In the early stage, study of the light transfer capability in vertical coupler had been carried out. It is found that due to the ridge waveguide structure used in the study, the vertical coupler exhibits unique characteristic that differentiates it from vertical coupler in other waveguide structures. It is found that the performance of the VC is highly polarization dependent. This shortfall, if remains unsolved, could limit the application of the VC because the input light could be randomly polarized. However, this problem is solved by designing a polarization independent vertical coupler, with the discovery of a unique inherited feature of the ridge structure. Aside from tackling the shortfall, the polarization dependent property could be utilized in designing a polarization splitter. These works not only expanded the application of vertical coupler in polarization control, but they are also the first to report about it.

Apart from the vertical coupler, a mode filter has also been designed. A mode filter is important to filter out the higher order modes that coexist in a waveguide, as some photonic devices could only work in the single-mode regime. The mode filter is constructed by simple lateral linear-tapered waveguides. It is differentiated from other mode filters reported in the literature by its simplicity, robustness and versatility. The

detailed study and simulations for verifying the concept, similar to what has been done for the vertical coupler designs has been carried out.

A polarization-independent coarse-wavelength splitter has also been designed. Although the design principle for coarse dual wavelength splitting (e.g., for 1.3 μm and 1.55 μm) is reported, polarization independence is hard to achieve. The splitter design is simple and is based on a ridge-type lateral directional coupler that can be readily integrated with other planar waveguide devices. While the basic design principle may not be new, the polarization independence of the filter design is novel and is shown to be achieved by exploiting the polarization sensitivity of the high-index contrast waveguides. We also show that the same approach can be easily applied to the design of polarization splitter based on directional coupler. The crosstalk, optical bandwidth and fabrication sensitivity for the wavelength filter are evaluated.

Beside the design works, some fabrication processes are studied and developed. The processes involved are learnt and optimized to obtain a consistent fabrication results. Amongst the processes, the room temperature InP dry etching using inductively coupled plasma is studied using the Taguchi's method for the first time. The room temperature etching process allows a shorter process cycle and lower equipment cost, while able to give comparable results with those done at elevated temperature. The mesa structure obtained has almost 90° sidewall, and the substrate surface is smooth (root-mean-square (RMS) roughness < 10 nm). The ridge waveguides fabricated using the optimized processes are measured in terms of propagation loss.

Quantum well intermixing is another important process that will be used in the fabrication of integrated active-passive devices. Hence, we have conducted study on the quantum well intermixing, by comparing the results obtained from two different techniques, i.e., the impurity-free vacancy disordering and the ICP plasma-enhanced intermixing, on our wafers. Suitable technique will be employed in our fabrication of integrated devices.

Eventually, two simple integrated photonic devices have been carried out. The fabrication processes learnt are utilized in realizing the device integration. The fabrications are carried out in the cleanrooms available in NTU and IMRE. The measurement of the fabricated devices is done in NTU.

1.4 Report Organization

In Chapter 2, the background information for better understanding the works carried out in the thesis is presented. Chapter 3 presents the design of the vertical couplers, Chapter 4, the design of the mode filter, and Chapter 5 the design of polarization-independent coarse wavelength splitter. The studies on the fabrication processes of photonic devices is, together with the optimization of the ICP dry etch process, is presented in Chapter 6. This is followed by Chapter 7, which elaborates on another important process for the fabrication of integrated devices, namely the quantum well intermixing. In Chapter 8, the integration of photonic devices is described, along with the fabrication process involved and the measurement results. All these are followed by conclusion and recommendations for future work. Finally, the references and the author's publications are listed.

2

Background Information and Literature Survey

In this chapter, we will present some background information necessary for getting a better understanding on the research work carried out in the thesis. General knowledge and theory behind the various topics of the thesis, such as photonic waveguides, vertical coupler, lateral mode filter, coarse wavelength splitters, and also on the fabrication process of the photonic devices, are presented. Besides, the literature survey on these topics is also presented here, which provides an overview on the current status of the topics.

2.1 Photonic Integration

Photonic integration involves the integration of various photonic building blocks with different functionalities, be it active or passive, onto a single chip. There are basically three main architectures of integration, namely the discrete integration, hybrid integration and monolithic integration. In discrete integration, the devices are in distinct packages and integrated by using optical fibers. The overall system is large, while the cost is also very high. However, the user enjoys the flexibility of choosing the components from different manufacturers. For hybrid integration, different devices made of different materials are packaged together on the same wafer. The devices could be slotted into the designated grooves micro-machined on the wafer, or could be chip-bonded to the wafer [15]. The system area and cost are much reduced. However, since the devices are made of different materials, it raises the issue of material compatibility and the optical alignment between the devices. Monolithic integration represents the ultimate choice of photonic integration. In monolithic integration, the devices made of the same material are integrated onto a single wafer, also from the same material. This eliminates the issue of material compatibility and optical alignment since the devices are usually fabricated from the wafer itself. The system area and cost are the smallest amongst the three forms of integration.

The drivers for integration are similar to those in the microelectronics. Firstly, integration aimed to reduce the number of discrete devices that require packaging. This not only reduces the system cost, but also reduces the overall system area. As the number of discrete devices reduces, the maintenance of the system will also be easier and more efficient. The number of fiber interconnects, which contributes to significant amount of optical loss and cost, will likely to be reduced as well. Besides, with the miniaturization of system area, the power consumption will be reduced.

Amongst the various material suitable for photonic application, the III-V compound semiconductor—InP and its compound InGaAsP stand out as one of the most suitable material platforms for monolithic integration. The attributes that enable this are:

- They are able to support both passive and active optical functions, e.g., laser emission, optical modulation, optical switching and wave guiding.
- Their bandgaps correspond to the telecommunication wavelength window, i.e., 1300-1600 nm, and are tunable.
- Their electrical functionality are superior.
- Their high material index as compared to air enables smaller waveguides and devices. This is suitable for high density integration, and
- High quality lattice-matched, very thick or very thin epitaxial layers (few nanometers) can be grown with the current state of technology.

Various photonic integrated devices have been demonstrated with InP. The simplest PIC demonstrated is the spot-size-converter integrated laser [16-20]. Lasers integrated with electroabsorption modulators (EAM) to provide higher bandwidth in excess of 10Gb/s have also been demonstrated since more than a decade ago [21-24]. This exceeds the bandwidth achievable by the commercially available direct modulated laser for telecommunication. Following this, laser integrated with semiconductor optical amplifier (SOA) has been developed in 2002 [25]. However, these integrated devices have limited functionalities due to the low level of integration. PICs with higher integration level, which integrate laser arrays with multimode interferometer, SOA and EAM that constitute a multiple wavelengths source, have been developed [26-27]. Recently, transmitter and receiver chips that can operate from 100 Gb/s up to 1.6 Tb/s have been demonstrated [28-30]. The PIC incorporates over 50 functions on a single chip monolithically.

The advancement of PIC shows that it has a great potential to be widely utilized in various areas. In PIC, waveguides are the backbone in connecting the separated devices optically. There are many types of waveguides, with variations in geometry and material. In the next subsection, some of these waveguides will be described.

2.2 Photonic Waveguides

The simplest photonic waveguide is constructed by having a film with higher material index sandwiched between two layers with lower material index. The light is guided in the waveguide through total internal reflection (TIR). The light is reflected, instead of refracted, at the material interfaces and confined in the higher refractive index region denoted as the waveguide core. This is illustrated in 2-D in Fig. 2.1. TIR happens when the angle of incident light is larger than the critical angle of the interface, θ_c , which is given by the Snell's law as $\sin^{-1}(n_2 / n_1)$. The same principle applied for 3-D confinement, where the higher index material is surrounded by the lower index region. The lower index region is denoted as waveguide cladding.

Fig. 2.1. 2-D illustration for total internal reflection of an optical waveguide, showing how the light is confined in the waveguide core, which is represented by region 1.

Region 2 is denoted as the waveguide cladding. n —refractive index

The schematic for two of the commonly seen waveguides are shown in Fig. 2.2. These waveguides are rib waveguide and ridge waveguide. For a rib waveguide, the light is guided laterally by the loading effect imposed by the rib section. The lateral

confinement is relatively weak, and hence, it is not suitable for miniaturization and sharp waveguide bending. Nevertheless, since the rib waveguide is simple to fabricate and poses low propagation loss, it has been implemented in various devices since the early stage of photonic development [31-35].

Fig. 2.2. Schematic of a (a) ridge waveguide, and (b) rib waveguide, and their corresponding simulated fundamental mode profiles.

The ridge waveguide is another commonly seen waveguide. For ridge waveguide, the waveguide core is exposed to the surrounding in the lateral direction, and depending on the index contrast between them, the waveguide could have very strong confinement if the index contrast is high. This makes it a very suitable candidate for miniaturization and sharp bending. This type of high-index-contrast waveguide has been utilized in devices such as laser [36-38], multimode interferometer [39] and microresonator-based filters [40-41]. The microresonator radius constructed could be only a few micrometers in size with waveguide as narrow as $0.42\ \mu\text{m}$ [40]. For weakly guided waveguides, the bend radius could be up to millimeters. These make the waveguide a necessary backbone for high density integration. With these advantages in mind, we move on to present the literature study on the various building blocks for photonic integration, where we can also see these waveguides have been implemented in the building blocks.

2.3 Vertical Couplers

Vertical coupler, as the name implied, couples the light vertically between waveguides. Vertical coupler with asymmetric waveguides has been widely used as a spot-size-converter (SSC) or sometimes denoted as an optical mode transformer (OMT), which transforms the mode size of a particular light beam to the desired size. It is particularly popular to be integrated with semiconductor lasers [20, 42-46], where the mode size of a laser output is expanded to match the mode of a single-mode fiber (SMF). The objective is to reduce the fiber coupling loss and increase the misalignment tolerance, as the output mode of a laser is usually much smaller than the fiber mode. This scenario is illustrated in Fig. 2.3, where as seen the optical mode size of a laser diode is expanded through vertical coupling to a larger underlying waveguide before being coupled into a SMF. The SSC is bidirectional and so it can be used to improve the fiber coupling to a smaller photonic device (i.e., in reverse direction) as well. It is also integrated with other devices, such as with SOA and EAM [24] and with photodetector [47] (These devices are to be denoted as actual device).

Fig. 2.3. Illustration of light coupling from a semiconductor laser to a standard single mode fiber through a vertical spot-size-converter.

In the vertical coupler, it is a challenge to optimize the top waveguide for both device performance and vertical light transfer at the same time. This is because their

optimized performances usually require different waveguide dimensions. Therefore, in the literature, several variations of the vertical couplers had been proposed to tackle this problem. Generally, the actual device is attached to a taper waveguide, which decouples the light transfer region from the actual device. The taper waveguide can be optimized for maximum vertical light coupling, either by adiabatic transfer or resonant coupling through the variation of the waveguide volume, without sacrificing the performance of the actual device. The adiabatic transfer occurs when the waveguide volume is changed very slowly such that the light shifts, by mode evolution, from one waveguide to another without loss. The resonant coupling occurs when the optical phase of the two waveguides are matched, and the light oscillates between the waveguides periodically

The light transfer region could be of many variations: it could be of the same material with the actual device or different; it could be vertically tapered or laterally tapered; the taper profiles could be linear, exponential or other complex shapes theoretically. Besides, the whole structure itself can be constructed with different types of waveguides (e.g., ridge waveguide, buried waveguide or rib waveguide), or a combination of some of them. In practice, having variation in waveguide geometry is more common than having different materials because the required fabrication steps are much easier and feasible. And among the different taper profile, linear lateral taper is more commonly used due to the same reason. Fig. 2.4 presents some examples of vertical couplers found in the literature [48-49] that utilizes taper waveguides. The use of different structure of vertical couplers is dependent on the application. In particular, the SSC in Fig. 2.4(a) had been utilized in the polarization insensitive optical amplifiers [50] and multiple quantum-well lasers. Vertical taper waveguides as shown in Fig. 2.4(b) and Fig. 2.4(d) are not usually used, as the vertically taper structures are relatively difficult to produce precisely.

Fig. 2.4. Examples of vertical coupler with vertical taper and lateral taper in the ridge and the buried waveguide structures.

Aside from being used as a SSC at the input/output stage of photonic devices for fiber coupling improvement, the vertical coupler has also been proposed as wavelength filter, which is an important component for wavelength demultiplexing. One such proposed vertical coupler utilizes a uniform upper waveguide [51-53], where only the selected wavelength is transferred to the upper waveguide. Cross waveguides architecture had also been proposed [54-55], where only the desired wavelength couples vertically at their crossing point, as shown in Fig. 2.5. However, these wavelength filters have small fabrication tolerances (e.g., strict requirement on waveguide width and cross angle). Furthermore, the cross waveguides require complicated fabrication process, which may not be desired.

In short, the vertical coupler has proved to be useful as an input/output stage for many devices, either for fiber coupling improvement or for wavelength multiplexing. The vertical coupler has added advantages over other SSC, in that the two waveguides can be highly asymmetric (i.e., different cross sections and refractive indexes) without incurring tedious fabrication process. This provides a mean for vertical integration. A laterally linear-tapered waveguide is relatively easier to be

designed and fabricated than other taper profiles, even though their performances might be slightly different. Amongst the various waveguide structures, the ridge waveguide structure is also a more compact option without compromising fabrication feasibility.

Fig. 2.5. Schematic of wavelength filter utilizing the cross waveguides vertical coupler [54]. λ -wavelength.

From the literature, we found that there is a lack of discussion on the polarization effect of the vertical coupler. Although there are several studies on the polarization effect in taper waveguide alone [56-57], no similar study has been performed on the vertical coupler. Generally for the InP-based ridge waveguide, the wave propagation is polarization dependent. Since our vertical coupler is based on ridge waveguide, the polarization effect could deteriorate the performance of the vertical coupler if they were not taken into consideration. The light from different polarizations could couple differently to the top waveguide and incurring unnecessary loss. Furthermore, the polarization of the light from a SMF (assuming an optical fiber input to a photonic device) is usually unknown. Therefore, we proposed a study on the polarization effect of the vertical couplers, and we will present for the first time, two applications of the vertical coupler in polarization manipulation, namely the polarization-independent vertical coupler and the polarization splitter. No polarization-independent vertical coupler has been reported before, and it is only recently that some researchers have reported a similar vertical coupler based on silicon-on-insulator (SOI) [58], which cited

our work. Several other architectures have been proposed for polarization splitter, and they are discussed shortly.

For light propagating in a waveguide, we can always decompose the light into two polarizations, namely the Transverse Electric (TE) and Transverse Magnetic (TM) polarizations based on the direction of the dominant electric field. By convention, for the ridge waveguide, the TE usually refers to dominant electric field in the lateral direction, and the TM refers to the vertical direction. While a polarization-independent vertical coupler is required to transfer the light for both polarizations impartially, a polarization splitter is a useful device in separating these different light polarizations.

In the literature, several architectures for polarization splitter had been proposed. Amongst the architectures are lateral waveguide couplers [59-60], Mach-Zehnder interferometer [61-62] (as shown in Fig. 2.6(a)) and mode selective channel waveguides [63-65] (as shown in Fig. 2.6(b)). They are either based on InP compound semiconductor or Lithium Niobate (LiNbO_3) material. In these architectures, many of them are based on the birefringence effect of the devices, in which the effective indexes (optical phase) for both polarizations are different in the devices. These are introduced either by using birefringent material or by using birefringent structure. The different polarizations will then behave differently in the devices and get separated because of these differences. For the various architectures, some of them are relatively large, which will increase the integration area, while some of them require complicated and stringent fabrication process. Besides, for the device using LiNbO_3 , its application in monolithic photonic integration may be limited as the material is not able to provide active and passive functionality on the same platform.

Fig. 2.6. Schematic (top view) of polarization splitter using (a) Mach-Zehnder interferometer [62], and (b) mode selective channel waveguide [65]. P—polarization.

There is another polarization splitter architecture based on vertical transfer of light. The device is based on polymer vertical branching waveguide [66], as shown in Fig. 2.7. Only the desired polarization travels into the upper waveguide as the effective index of that particular polarization is the highest in the upper waveguide. The waveguide is almost invisible to the unwanted polarization, and hence it will continue to propagate in the lower waveguide. However, this method suffers the same drawback as LiNbO_3 based devices, in which it is impossible to integrate active and passive devices monolithically. Furthermore, the vertical branching waveguide with small branching angle requires very challenging fabrication process.

Fig. 2.7. Schematic of polymer vertical branching polarization splitter [66]

For the vertical coupler, its application as a polarization splitter could provide additional advantages over other architectures. As compared to the lateral coupler, the vertical coupler allows the interacting waveguides to be composed of different materials with just a single step epitaxial growth. The waveguides could have very different cross sections as well. Unlike the lateral couplers, the gap between the waveguides in vertical coupler is relatively easy to control. The InP platform used will also allow active and passive devices to be integrated monolithically. In all the polarization splitters discussed before, the contrast ratios (ratio of power for desired polarization over the unwanted polarization) range from 15 dB to 22 dB. Our proposed design, as we will show later, is able to provide comparable contrast ratio. A possible application of polarization splitters is in polarization-diversity detection, as illustrated in Fig. 2.8. With our designs, the vertical coupler is able to be utilized in more applications other than merely as a SSC for fiber coupling improvement.

Fig. 2.8. Illustration of polarization-diversity detection employing the vertical coupler polarization splitter. P—polarization.

2.4 Lateral Mode Filters

As mentioned previously, high index contrast waveguides such as ridge waveguides have been widely used in device interconnects and in constructing photonic devices. This is due to the strong lateral confinement of the waveguide,

which allows sharper bending and narrower width as compared to other waveguides. Despite the advantages of using high index contrast waveguides, one of the problems is the difficulty in constructing a single mode waveguide, which is required by many devices such as the directional coupler and Mach-Zehnder interferometer. A high index contrast waveguide is generally multimode horizontally due to the high index contrast interface, even though vertically, it can be made single-mode easily by having a small cladding-core index difference. Although the excitation of higher order mode in the waveguides could be suppressed by improving the sidewall smoothness, fiber input misalignment and waveguide bending could also excite the higher order mode. A laterally single-mode high index contrast waveguide is typically hundreds of nanometers in width, which could incur other problems—high propagation loss over long distance and high fiber coupling loss due to the small dimension. Hence, a wider waveguide is often used at the expense of the single-mode characteristic. All these have imposed a need of mechanism for higher order mode filtering.

Several architectures had been proposed for higher order mode filtering in planar waveguides, such as by using multimode interferometer (MMI) [67-69], non-identical waveguides coupler [70], total internal reflection (TIR) mirrors [71], asymmetric Y junction [72-74] and few millimeters long waveguide [75]. Some examples of these mode filters are shown in Fig. 2.9. The mode filters generally utilizes the different effective indexes of the guided modes. Generally, the higher the mode order, the lower the effective index. Lower effective indexes mean that the higher order modes: (i) propagate in highly lossy manner and dissipated when propagating through a junction; (ii) reflect at different angles at the TIR mirror; (iii) self-image at different distance in MMI; and (iv) have different coupling length in waveguide coupler. Nevertheless, the small fabrication tolerance (e.g., the length of the MMI; the small branching angles of the multi-branches waveguide; the alignment of TIR mirror) or

fabrication complexity (e.g., the multiple branches of the junction filter) could limit their application as a mode filter.

Fig. 2.9. (a) Side view of the vertical Y junction waveguides mode filter [72], and (b) top view of a MMI mode filter [69] that show the mode field profiles of the propagating wave at different location of the devices.

Some filter architectures had also been proposed for multimode fiber optic, for example by using higher index coating [76]. Nevertheless, the method is difficult to be realized in planar waveguide structure as precise selective-area edge-and-regrowth is required. In this thesis, we proposed a higher order mode filter by using a single growth back-to-back laterally linear-tapered waveguides structure, which could be cascaded to any ridge waveguide to filter off the higher order modes. The architecture is very simple. Although similar architecture had been proposed for multimode fiber optic [77], no application on high index contrast planar waveguide had been reported.

2.5 Wavelength Splitters

Wavelength division multiplexing (WDM) and demultiplexing are important functions in optical communications. In optical communications, different wavelengths can be used to carry different information through the same optical fiber link without any crosstalk. The optical signals of multiple wavelengths are combined (multiplexed) into the common fiber link at one end and separated (demultiplexed) into individual component at another end.

In coarse wavelength division multiplexing (CWDM), the number of channels is fewer than in dense wavelength division multiplexing (DWDM). CWDM systems have channels at wavelengths spaced 20 nm apart, compared with 0.4 nm spacing for DWDM. The wavelengths range from 1271 nm to 1611 nm according to the International Telecommunication Union (ITU) grid [78]. The wavelength tolerance in a CWDM laser is up to $\pm 6-7$ nm, whereas in a DWDM laser the tolerance is much tighter. Therefore, CWDM allows the use of un-cooled lasers with lower precision and wide pass-band filters, and this makes the CWDM system less expensive and consumes less power than a DWDM system. However, the maximum realizable distance between nodes is smaller with CWDM. CWDM system can be used in transport networks in metropolitan areas for a variety of clients, services and protocols. In some literature, it has been proposed that the 1300 nm and 1550 nm wavelength regions are used to carry data/voice and video, respectively in the fiber-to-the-home (FTTH) applications [14].

Since the wavelengths in CWDM are spaced far apart, a CWDM filter is needed to separate or combine the wavelengths. A bidirectional and compact filter that can be integrated with transceivers is desirable, as it would facilitate the development of low-cost terminal units for the home. Therefore, the filter should ideally be based on integrated optics, be polarization independent, have large optical bandwidth and low crosstalk. An integrated optic realization of the ubiquitous fused fiber coupler is the waveguide directional coupler (DC). A dual-wavelength splitter for 1300 nm and 1550 nm based on such a directional coupler has been demonstrated in SiGe/Si waveguides, but it is relatively large in size and works only for one polarization [79]. It should be noted that the requirements and design of the CWDM waveguide filter are very different from the narrowband or dense WDM (DWDM) waveguide filters, which are relatively complex and found in various forms based on vertical asymmetric waveguide couplers [51]-[53], arrayed waveguide gratings [79], cascaded Mach-

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Zehnder interferometers [80], and many more. In the thesis, we show theoretically that compact and polarization-independent dual-wavelength splitters based on a single lateral directional coupler are possible for both the InGaAsP/InP and SiGe/Si material systems. The design is based on strongly confined, high-index contrast ridge waveguides, as opposed to the conventional weakly-guided, low-index contrast, rib or buried waveguides used in most other designs. Paradoxically, the key to achieving polarization independence is to utilize the strong waveguide birefringence inherent in these high-index-contrast waveguides.

2.6 Photonic Waveguides Fabrication Process

2.6.1 General Fabrication Process

For photonic waveguides or devices based on compound semiconductor material, the fabrication processes are adopted from the fabrication of silicon electronic IC. This is because the fabrication processes of silicon microelectronics have long been mature and the equipment available is abundant. The processes could also be optimized to suit the compound semiconductor. In general, the main fabrication steps of a photonic waveguide involve epitaxy growth of the different material layers and the patterning of the epi-substrate. The more detail process flow of making a ridge waveguide is shown in Fig. 2.10.

The process usually starts with the material growth, which will create the layers of waveguide core and claddings that are needed for light guiding. In compound semiconductor waveguide, the layers are grown epitaxially. Epitaxy is defined as the deposition of some material layers on a substrate, all having similar single crystal lattice structure. The lattice constant of the layers and the substrate must be closely matched, and this is denoted as 'lattice-matched'. Several technologies are used to

grow the epitaxy layers nowadays. They are: (i) Liquid Phase Epitaxy (LPE), (ii) Molecular Beam Epitaxy (MBE), and (iii) Metal-organic Chemical Vapor Deposition (MOCVD), each having their own advantages and disadvantages. They are differentiated by the status of the sources used in the growth.

Fig. 2.10. Process flow for fabricating a semiconductor ridge waveguide

After the layers have been grown, the epi-substrate will be patterned with the designed structure. Etching is an important step to define the structures, whereby it will etch away the unblocked area to a desired depth. The blocked area will typically be covered with photoresist or dielectric. In our case, we chose dielectric silicon dioxide (SiO_2) because it is mechanically and thermally more stable than the photoresist. The SiO_2 is deposited onto the substrate through plasma-enhanced chemical vapor deposition (PECVD). The material is deposited by the plasma-assisted chemical reactions between the source gases on the top surface of the substrate. The SiO_2 deposited by PECVD is denser than those deposited by other methods such as spin-on-glass and electron beam evaporation, and hence, it is more effective in blocking the plasma. However, the dangerous source gas used, silane (SiH_4) may incur additional safety cost. But, with proper working procedures and facilities in place (e.g., burn box), this problem can be solved.

With SiO_2 coated on the substrate, the actual patterns need to be transferred to the SiO_2 before etching. For this purpose, photolithography, followed by oxide etching, will be carried out to transfer the desired patterns to the SiO_2 . Photolithography involves the use of ultraviolet (UV)-sensitive material, called photoresist, that will be exposed with UV passing through a pre-fabricated photomask. The photomask contains the patterns to be transferred, usually defined by chromium (Cr) on quartz/glass substrate. The chromium is opaque to the UV light, while the quartz/glass is transparent to the UV light. If positive photoresist is used, then the exposed region will become soluble in the resist developer; if negative photoresist is used, the unexposed region will become soluble in the developer. The photoresist will then be used as the etch mask for etching SiO_2 . The photoresist pattern is then transferred to the harder SiO_2 layer. After the photoresist is removed, the SiO_2 is then used as etch mask to etch the underlying substrate.

2.6.2 Dry Etching of Waveguides

For the fabrication of photonic waveguides or devices, dry etching is often essential to obtain the precise dimensions and highly anisotropic structural profile required. This is because of the combined physical bombardment (anisotropic) and chemical reaction (isotropic) between the etchants and the target material in dry etching, which enable the possible production of 90° vertical sidewall. As compared to wet-etching, which is dominated by chemical reaction, the sidewall is usually rounded because the chemical reaction is isotropic. A comparison of the etching profiles between the dry etching and the wet etching are shown in Fig. 2.11.

Fig. 2.11. Photographs taken by Scanning Electron Microscope (SEM) on the etched profiles from (a) wet etching, and (b) dry etching.

In dry-etching, the etchants are available in the form of plasma, which is a glowing quasi-neutral mixture of electrons, ions and neutral species. Various plasma etchers, such as reactive ion etcher (RIE), electron cyclotron resonance (ECR) and inductively-coupled plasma (ICP) have been utilized. In these plasma etchers, the plasma is generated by applying a high radio frequency power, typically around 13.56 MHz with hundreds of amplitude, to a gas mixture at low pressure in between two electrodes. One electrode is normally formed by the chamber wall, while another formed by the wafer stage. The high power oscillation will strip the gas molecules of electrons, and the electrons are pulled towards one of the two electrodes in each half cycle. When the electrons reach the chamber wall, it will be grounded and leaves behind plasma with positively charged species. When the electron reaches the wafer stage, it will accumulate due to its direct current (DC) isolation and form a negative bias. With this, the positively charged species are attracted to the substrate vertically. These species will either chemically react with or sputter off the substrate surface. The products will then escape to the low vacuum environment. The products must be volatile enough in order to be removed successfully from the substrate surface.

RIE is the most basic form of plasma etcher. ECR and ICP are variations of RIE. For ECR, it incorporates microwave power with a static magnetic field to force

electrons to circulate around the magnetic field lines at an angular frequency. This increases the collision probability, allowing the generation of higher density plasma. For ICP, plasma is formed in a dielectric vessel surrounded by an inductive coil. RF power is applied to the coil, and this produces an electric field in the vertical direction. The electrons will be trapped in the centre of the chamber and generating high density plasma. At low chamber pressure, the plasma will diffuse into the chamber and drift towards the substrate. For both ICP and ECR, a RF-bias is superimposed onto the wafer stage to control the ion energy. ICP and ECR are advantageous over RIE because they are able to excite higher density plasma, and to provide independent control of the ion energy and plasma density. On the other hand, ICP is advantageous over ECR because it is relatively simple and more economical for production [81].

Dry-etching has been used for the fabrication of various waveguide-based devices [82-87]. Different chemistries, such as CH_4/H_2 [88-93], Cl_2 (with different additives) [94-98], SiCl_4 [99], BCl_3 [100] and N_2/H_2 [101] have been demonstrated for etching InP. The most widely used recipes are based on CH_4 and Cl_2 . For the conventional CH_4/H_2 chemistry, good surface and sidewall qualities can be obtained, but the polymer formation and low etch rates could be problematic. For the chlorine-based recipes on InP, the polymer formation is avoided and the etch rate is much improved, but the reaction products are non-volatile unless the substrate is heated to around 200°C or more. The need for heating incurs additional cost and process time, and limits the etch mask to dielectric materials or metals (photoresist cannot be used at such high temperatures).

In ECR, $\text{Cl}_2/\text{CH}_4/\text{H}_2$ [102] and BCl_3 [100] etching of InP using ECR has been reported at a temperature of $\sim 150^\circ\text{C}$, and the etch rates obtained were 250 nm/min and 800 nm/min, respectively. Cl_2/Ar and $\text{Cl}_2/\text{CH}_4/\text{Ar}$ etching of InP using ECR [103] and ICP [104], respectively, at room temperature have been reported, but the physical

bombardment by the heavy Argon ions ($Z=40$) could cause significant surface damage. In the thesis, we report for the first time the optimization of ICP etching of InP in $\text{Cl}_2/\text{CH}_4/\text{H}_2$ and Cl_2/N_2 gas mixtures under room temperature condition. The results, in terms of etch rate, surface roughness and etched profile, are compared.

2.6.3. Quantum Well Intermixing

Quantum well structure on InP-based compound semiconductor is formed by having an epilayer with thickness comparable to the de Broglie wavelength of the carriers, i.e., electrons and holes, sandwiched between other epi-layers (quantum well barriers) with wider bandgap. This creates a two dimensional quantum confinement of the carriers, leading to discrete energy subbands and sharper density of states than bulk material. Quantum well structure is widely used for fabricating active devices that involves carrier recombination such as lasers, photodetectors, modulators and etc.

In monolithic integration, active and passive regions need to be integrated onto a single substrate. For example, a modulated laser diode can be integrated with a passive waveguide so that the signal can be distributed to the desired location on the same chip. Passive waveguide is preferred for signal distribution because it will incur less propagation loss than active waveguide, which usually poses bandgap energy near to or smaller than the signal energy. Thus, this imposes a need to create quantum wells with different material bandgaps on a single substrate.

Several techniques have been proposed for this purpose, for example etch-and-regrowth, selective-area-growth and etc. Amongst all these techniques, quantum well intermixing is one of the most promising methods. It is a post-growth bandgap manipulation technique, which enables localized bandgap tuning of quantum wells. As compared to other techniques, the process step is simple and it doesn't incur scattering and reflection losses at the interface of the different regions due to material mismatch.

There are various methods for realizing QWI, for example the impurity-free vacancy diffusion (IFVD) [7,11], argon plasma-enhanced [9], ion implantation [10] and laser-induced disordering [105]. Most of the methods involve generating defects in the material structure through different techniques, and then followed by rapid thermal annealing (RTA) treatment that promotes the inter-diffusion of the defects and atoms. As the atoms diffuse and rearrange themselves, the material compositions of the quantum well and barriers change, and this modifies the bandgap. With the bandgap changes, the absorption spectrum of the quantum wells are changed. If the bandgap shrinks, this is denoted as redshift, but if the bandgap expands, this is denoted as blueshift (as the emission wavelength decreases). Fig. 2.12 illustrates a scenario where laser light with a particular energy/wavelength will be absorbed in the original material but becomes transparent to the intermixed material after the bandgap blueshift. However, in some techniques, the defects generated could degrade the crystal quality and the optical properties of the material.

Fig. 2.12. Effect of QWI on the bandgap profile and the photon absorption behavior of a blueshifted material

Among the various QWI techniques available, IFVD is one of the most promising methods. It is simple and it does not induce excessive crystal damage to the material, i.e., less optical loss to the device. IFVD involves the deposition of a dielectric cap layer, such as SiO_2 or Si_3N_4 , onto the quantum well substrate, followed by RTA which promotes the inter-diffusion between the vacancies and atoms. The vacancies could

be generated on the substrate during the dielectric deposition stage. Depending on the dielectric material, it could encourage or inhibit the intermixing. The difference in the thermal expansion coefficients of the dielectric and the top layer of the substrate plays an important role. The thermal expansion coefficients of the dielectric and III-V compound semiconductors that are used in our research are shown in Table 2.1 for reference. If the substrate surface is under compressive stress during annealing, i.e., the thermal expansion coefficient of the dielectric cap is smaller than that of the top layer of the substrate, the vacancies will diffuse across the quantum well region and promote intermixing. If it is under tensile stress, the vacancies will be trapped and hence, the intermixing is limited [106]. Due to the advantages of IFVD, it is utilized in the demonstration of passive-active devices integration in the latter part of the thesis.

Table 2.1. Thermal expansion coefficient of various dielectrics and III-V compound semiconductors at 300K. The ternary InGaAs and quaternary InGaAsP presented are lattice-matched to InP [106-108].

Material	Thermal Expansion Coefficient α_{th} ($\times 10^{-6}/^{\circ}\text{C}$)
SiO ₂	0.52
Si ₃ N ₄	3.30
InP	4.56
GaAs	6.40
In _{0.53} Ga _{0.47} As	1.08-1.10
In _{1-x} Ga _x As _y P _{1-y}	1.18y+ $\alpha_{th}(\text{InP})$

As an example of active-passive integration, we designed and fabricated a simple PIC consisting of a multimode interferometer (MMI) 1 by N splitter and electroabsorption modulators (EAM) at each of the N outputs of the splitter. This integrated device functions as a 1×N switch, where each output is attenuated when the modulator is highly absorptive. The modulator can also be forward biased to act as an amplifier if the end-facet is also anti-reflection coated. On the other hand, the

MMI is a passive device and hence must be transparent at the operating wavelength. This transparency is achieved by expanding the bandgap in the MMI region using quantum well intermixing while leaving the bandgap relatively unchanged in the EAM region. Below in the last section we give an overview of EAM.

2.7 Electroabsorption Modulator (EAM)

In optical communications, light is always modulated to carry information. The modulation could be on the phase, the intensity, the frequency or the polarization of the light. Intensity modulation is the most commonly used scheme because of the simplicity in envelope detection. A laser source can be directly modulated by the current supply to achieve this purpose, which represents the simplest form of intensity modulation. However, with the increasing need of longer communication distance and higher modulation frequency ($>20\text{GHz}$), the direct modulation has reached its limit due to the frequency chirp, signal noise and distortion [109-110].

External modulation is preferred as it is able to provide higher modulation frequency, lower signal noise and frequency chirp. Several types of optical intensity modulator have been developed. They are mainly based on the electrooptic (EO) effect and electroabsorption (EA) effect. Electrooptic effect involves the change of optical refractive index in nonlinear optical crystals due to the applied electric field. The index change will lead to the change of optical phase, which in turn lead to intensity modulation. One popular example that utilizes the electrooptic effect is the Mach-Zehnder interferometer [111]. To construct an EO modulator, the material must exhibit EO effect under the application of electric field. Lithium Niobate (LiNbO_3), III-V semiconductor and polymers are the suitable candidates for this. However, EO modulators tend to be longer due to the required accumulated phase difference, and

for monolithic integration, the only suitable candidate—III-V semiconductor has relatively small EO coefficients.

Electroabsorption effect denotes the change of optical absorption coefficient of material due to an applied electric field. The EA modulator could be as simple as just a single waveguide, and the length is much compact than the corresponding EO modulator from the same material. Currently, the primary material for EA modulator is III-V compound semiconductor, which makes it easier for monolithic integration. An EA modulator is usually consists of p-i-n semiconductor layers, which have intrinsic layers having higher material index than the p- and n-type layers. This is to provide the vertical light confinement needed for the modulator. The intrinsic layers also have the smallest bandgap energy, which is slightly larger than the energy of incident light. Therefore, when no electric field is applied, the light passes through with little absorption, but, under an electric field, the light will be absorbed. There are basically two types of EA effects, namely the Franz-Keldysh effect for bulk material, and quantum-confined Stark effect (QCSE) for the quantum well structure. In the thesis, we utilize the QCSE; hence, it is briefly described here.

Quantum-confined Stark effect exists in quantum well structure, where both electrons and holes are confined in a narrow well with discrete energy levels called subbands. The density of states becomes a step function, which is different from the square-root function of bulk material. Furthermore, the confined electrons and holes are electrically bound as excitons, which have smaller Bohr radius and higher binding energy than that of bulk material. This enables the exciton peak to appear even at the room temperature. An example of the absorption spectrum is shown in Fig. 2.13(a). The peaks are due to the exciton transition energy. Under an electric field, the quantum well will be tilted, and the effective bandgap is changed. This is illustrated in Fig. 2.13(b)-(c). The exciton linewidth is also broadened and the peak will be redshifted, as shown in Fig. 2.13(a). These two contribute to a larger change in the

absorption spectrum at longer wavelength than the bulk material. Hence, the QCSE quantum well structure is preferred for a more efficient EA modulator that is used in our PIC subsystem.

Fig. 2.13. (a) Simulated absorption spectra for a single quantum well under different electric field, F , and (b) the band diagram illustrating the effect of electric field [109].

E_{h1} —first hole energy level; E_{e1} —first electron energy level.

With these foundation laid, we will proceed on to discuss about the actual works done in the thesis.

3

Design of Vertical Couplers for Polarization Independent Coupling and Polarization Splitting

In this chapter, we will discuss about the design works for one of the building blocks in photonic integration. The device is a vertical coupler, or sometimes being denoted as spot-size-converter. The vertical coupler has been widely reported in the literature due to its potential in reducing the input fiber coupling loss to an actual device, and also in enabling high density 3-D integration. However, no report has been done on the polarization dependent aspect of the vertical coupler so far. Hence, we will look into this aspect, and as we will show later, we have designed a polarization-independent vertical coupler and a polarization splitter based on asymmetric ridge waveguides vertical coupler. All these have utilized the polarization dependent behavior of the ridge waveguide. We will also present some discussions on a three-level vertical coupler, and also a single-mesa vertical coupler, which is different from the conventional double mesa vertical coupler encountered so far.

3.1 Principle of Vertical Coupling

The working principle of the vertical coupler is similar to that of lateral waveguide coupler. Generally, the wave propagating in one waveguide can tunnel into the other waveguide through the evanescent wave that extended into that particular waveguide. The existence of evanescent wave in the cladding region is caused by the finite difference of the refractive indexes between the core and the cladding. To illustrate the working principle of a general waveguide coupler, we consider two waveguides located in close proximity, as shown in Fig. 3.1. Here, we assume a single input is injected into waveguide 1.

Fig. 3.1. A general waveguide coupler with two waves, E_1 and E_2 propagating in the waveguides having propagation constants β_1 and β_2 , respectively. $\Delta\epsilon$ represents the perturbation in the permittivity of the waveguide materials.

The two interacting waves can be described by the coupled mode equations [112]

$$E_1(z) = E_1(0)e^{j2\Delta\beta(z)z} \left[\cos\{s(z)z\} + j \frac{\Delta\beta(z)}{s(z)} \sin\{s(z)z\} \right] \quad (3.1)$$

$$E_2(z) = -j \frac{\kappa_{21}(z)}{s(z)} E_1(0) e^{-j2\Delta\beta(z)z} \sin[s(z)z], \quad (3.2)$$

by assuming $E_2(0)=0$ since we usually have only one input, and

$$\kappa_{12}(z) = \frac{k_o^2}{2\beta_1(z)} \frac{\int \Delta\epsilon_1(z) \mathbf{U}_1^*(z) \cdot \mathbf{U}_2(z) dA}{\int |\mathbf{U}_1(z)|^2 dA}$$

$$\kappa_{21}(z) = \frac{k_o^2}{2\beta_2(z)} \frac{\int \Delta\epsilon_2(z) \mathbf{U}_2^*(z) \cdot \mathbf{U}_1(z) dA}{\int |\mathbf{U}_2(z)|^2 dA}$$
(3.3)

$$s(z) = \sqrt{\Delta\beta(z)^2 + \kappa_{21}(z)\kappa_{12}(z)}$$
(3.4)

$$\Delta\beta(z) = \frac{1}{2}[\beta_1(z) - \beta_2(z)],$$
(3.5)

where κ_{ab} is the coupling coefficient from b to a, $\mathbf{U}$ is the normalized transverse mode profile, A is the cross-sectional area, k_o is the free space wave number and β is the propagation constant.

To obtain a maximum transfer of light from waveguide 1 to 2, we would like $\Delta\beta \approx 0$ (i.e., $\beta_1 = \beta_2$) as can be seen from Eq. (3.2), which is denoted as the phase matching condition. Under this condition, the light is coupled resonantly into the other waveguide, and the power transfer as inferred from Eq. (3.2) is

$$\frac{I_2(z)}{I_1(0)} = \left| \frac{E_2(z)}{E_1(0)} \right|^2 = \sin^2[\kappa(z)z]$$
(3.6)

by assuming $\kappa_{12} = \kappa_{21} = \kappa$, where we can see that the power transfer is depending on the coupling coefficient, which in turn depends on the overlapping of the two waveguide modes. The higher the overlapping, (i.e., the closer the waveguides or the weaker the light confinement in the waveguides) the stronger the coupling. The light coupling will occur in a sinusoidal fashion between the two waveguides. The resonant coupling enables the light coupling to occur within a shorter distance as compared to adiabatic coupling, and hence, the overall device size will be much shortens. Therefore, the light coupling in our vertical coupler design will be mainly contributed by the resonant coupling.

Generally between two dissimilar waveguides, the phase matching condition does not always occur. The condition $\Delta\beta \approx 0$ only occurs when the effective index of the two waveguides are approximately the same. This could be controlled by varying the waveguide parameters (e.g., layer thickness, waveguide width and etc.) of one or both of the waveguides, such that the condition will be satisfied over a specific region. At this region, the light will then coupled sinusoidally between the two waveguides. With this method, it allows us to construct a coupler using two highly asymmetric waveguides, which gives greater flexibility in designing the two waveguides for photonic integration. For example, one waveguide could be passive and have larger cross section, while another waveguide could be active and have much smaller cross section. This is clearly an advantage over the conventional directional coupler, in which two identical waveguides are used. Additionally, since in practice the material index is not known precisely, the use of slowly varying waveguide, such as the lateral taper waveguide in which the effective index varies with distance, offers better tolerance to a slight deviation of the actual material index.

In the actual application, the device usually accepts input from a SMF, in which the light polarization is unknown due to the symmetric structure. The different polarizations could transfer differently to the top waveguide, and this will incur unnecessary loss to the optical signal. Thus, this imposes a need for a polarization-independent vertical coupler, which is not presented in any literature before.

3.2 Design of Polarization-Independent Vertical Coupler

3.2.1 Design Structure and Principle

Our vertical coupler structure is formed by two asymmetric waveguides one on top of another, separated by a thin spacer layer. The whole structure is formed with

ridge waveguides. An actual device, which the fiber coupling to the device is to be improved, is assumed to attach to the top waveguide. Hence, the core thickness and material of the top waveguide is usually predetermined by the actual device. The underlying waveguide has a larger and squarer core, such that the mode field becomes more symmetrical and improves the fiber coupling. In our application, the material system is InP-InGaAsP, with InP forming the claddings and the spacer layer, while InGaAsP forming the waveguide cores. The top waveguide is laterally linear-tapered and light transfers up or down at the transfer regions. The transfer region is sandwiched by two steeper taper regions, as shown in the schematic in Fig. 3.2. The first steep taper is to avoid the abrupt change of structure as seen by the light, and the second steep taper is to expand the waveguide width to that of the actual device.

Fig. 3.2. Schematic of vertical coupler attached to a photonic device.

For a given combination of core index and core thickness, the effective index of the top waveguide is a function of width and polarization only. An example of the calculated effective indexes curve of the waveguides in VC is represented by Fig. 3.3. The top waveguide core is assumed to have a material index of 3.30 and thickness of $0.50\ \mu\text{m}$. The top cladding is assumed to be $1.5\ \mu\text{m}$ thick. The underlying waveguide core is assumed to have a material index of 3.19 and cross section of $4 \times 3\ \mu\text{m}^2$. Since the bottom waveguide has a uniform width and relatively symmetric cross section, the effective index is insensitive to the different polarizations; hence, the effective index of

the bottom waveguide is shown to be constant and the same for TE and TM polarizations.

Fig. 3.3. Effective index of the individual waveguide at various taper widths for TE and TM polarizations.

As mentioned before, in our vertical coupler design, we rely mostly on the resonant coupling for the light transfer, and it occurs when the effective indexes of the two asymmetric waveguides become nearly identical. This is also shown in Fig. 3.3, where it is represented by the intersection points between the effective index curves of the two waveguides. The widths of the tapered top waveguide at these intersection points are denoted as resonant widths, which are the widths that the phase matching condition is satisfied for the two interacting waveguides. The top waveguide will then be designed to be slowly tapered and embracing the resonant widths at some point in between. Slow taper is preferred so that the phase matching condition is satisfied over a longer distance to maximize the vertical coupling of light. However, the resonant width is generally different for different polarizations, which means that their maximum transfers occur at different points along the taper. If these two points are far apart, then their inclusion within the taper will require a longer taper, or a taper with

greater slope, which is undesired as the phase matching condition will be satisfied only over a smaller region. Hence, it is advantageous to have the same resonant widths for both polarizations.

To fulfill the above requirement, we need to utilize a width where the top waveguide has the same effective index for both polarizations. This is denoted as the critical width in Fig. 3.3, which is the width where the effective index curves of the top waveguide intersect. At this point, the top waveguide is said to be polarization-independent. The mode profiles of the two polarizations are almost identical at this width, as shown in the insets of Fig. 3.3. Hence, to have the same resonant width for both TE and TM polarizations, it is obvious that the resonant widths must coincide with the critical width. This represents an important requirement in designing a polarization-independent vertical coupler.

The effective index of an InP-based ridge waveguide is usually polarization dependent, and the existence of critical width is a unique characteristic of a ridge waveguide. This is due to the ridge waveguide structure, which causes the dominant electric field of both polarizations to see different materials in their directions (e.g., InGaAsP-air interface laterally and InGaAsP-InP interface vertically in our case). The effective index of the TE polarization is more sensitive to the increase of width since its mode field is extended more laterally. The TM effective index is not as sensitive because the mode field is extended more vertically. Therefore, when the width is small, the TE effective index is smaller than that of TM, but, as the waveguide width increases, the TE effective index will increase faster until a threshold width where the TE effective index eventually exceeds the TM effective index. At the intersecting width, the mode fields of both polarizations are very similar, and the width at this point is the critical width.

In short, as a rule of thumb for the design of polarization-independent VC, the transfer region should be slowly tapered and embracing the critical width, so that a

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compact device with maximized polarization-independent vertical coupling could be achieved. This is the first time that a polarization-independent VC is reported based on the unique characteristic of the ridge waveguide.

3.2.2 Design of the Underlying Waveguide

Fig. 3.4. (a) Critical widths, and (b) the corresponding effective indexes at the critical widths for the different combinations of core thickness and refractive index for the top waveguide core. The color bands represent the different ranges.

As explained previously, the most important step in designing a polarization-independent VC is the determination of the waveguide structures that will match the

resonant widths with the critical width. For this, the critical width of the top waveguide with a particular configuration must be known. The critical width is generally dependent on the waveguide core index and thickness, which in turn depend on the actual device. In Fig. 3.4, we have calculated the critical widths and the corresponding effective indexes of the top waveguide for various combinations of core thickness and refractive index. These figures are useful in deducing the critical width for a given core thickness-refractive index pair of the actual device. The resonant widths can then be matched with the critical width by adjusting the effective index of the underlying passive waveguide.

The effective index of the underlying waveguide is determined by its cross section and material index. The thickness of the waveguide will determine the effective distance between the centroid of the guided mode for the interacting waveguides. Intuitively, the greater the thickness, the more the light beam would have to shift its mode centroid vertically. Also, the overlapping of evanescent wave will be reduced. This will reduce the vertical transfer of light. However, small thickness will reduce the fiber coupling. Thus, as a compromise and also from the simulations, 3 μm is chosen as a value that gives sufficient overlap of the lower waveguide mode with the fiber mode and also with the upper waveguide mode. Likewise, wider waveguide means wider mode spread in the horizontal direction. Therefore, the vertical mode overlap of the waveguides will be less. But, narrower waveguide will reduce the fiber coupling efficiency. It is found that the effective index is quite insensitive for width of 3-5 μm (about 0.01 increments from 3 μm to 5 μm); hence, the waveguide width is assumed to be 4 μm . After the cross section of the underlying waveguide is determined, the effective index will be a function of material index only. The effective indexes for various material indexes are shown in Fig. 3.5, which can be used together with Fig. 3.4 to design a polarization independent vertical coupler.

Fig. 3.5. Effective indexes of the various refractive indexes for the underlying waveguide core with cross section of $4 \times 3 \mu\text{m}^2$.

3.2.3 Design of the Tapered Top Waveguide

The top waveguide is laterally linear-tapered. The tapering increases the robustness of the vertical coupler as compared to the use of uniform waveguide. This is because it allows larger deviation in the resonant width, which could be caused by the uncertainty in refractive index. The taper waveguide must start with a reasonably small width to avoid a non-adiabatic jump in the effective index of the lower waveguide due to the presence of the top waveguide. This width could be increased rapidly to the initial width of the taper over an initial buffer region, which should be as short as possible in order not to affect the light transfer. Nonetheless, it must not be too short due to the fabrication consideration. Hence, it is set as $30 \mu\text{m}$ while maintaining the compactness of the vertical coupler in our design.

Within the transfer section, the taper width is increased slowly from the initial width to the final width over a transfer length. The taper waveguide is designed such that the phase matching condition occurs within the taper for both polarizations. The taper must be slow enough in order to allow sufficient distance for complete resonant

coupling to the top waveguide. For polarization independent light transfer, the taper waveguide must embrace the critical width, which is also the resonant widths for this design, and it could be determined from Fig. 3.4 and Fig. 3.5. Simulations show that, for a given taper length, power transfer from the lower waveguide begins some width smaller (typically within $0.3\ \mu\text{m}$) than the critical width, and reaches the maximum a width slightly larger (typically within $0.05\ \mu\text{m}$) than the critical width, with the transfer occurs earlier and faster for the TM polarization. This is because the TM polarization, which mode field is more elongated vertically, has a greater coupling coefficient than the TE polarization. For the transfer length, we assume it to be $150\ \mu\text{m}$ as it is found to be the most compact possible. The detail of this selection will be explained later.

After the final width, the waveguide width is increased rapidly to the width of the actual device over another buffer region. This buffer region transforms the waveguide mode in the transfer region to that of the actual device. It is also responsible to invalidate the phase matching condition and cut-off any back-coupling of light to the underlying waveguide. Besides, the steep taper increases the effective index of the top waveguide and helps to attract more light to the top waveguide. The exact lengths of the both buffer regions are not critical; hence, they will not be discussed in detail. Nevertheless, $30\ \mu\text{m}$ is chosen for the second buffer region to: (i) maintain the compactness of the device, (ii) provide a smooth mode transformation, and yet be able to (iii) nullify the phase matching condition so that the light will stay at the top waveguide. Emphasis will be given to the optimization of the vertical transfer region (i.e., initial width, final width and taper length). To better illustrate the changes of effective index along the various regions, the effective index change along the longitudinal distance of the VC is sketched in Fig. 3.6.

Fig. 3.6. Sketches of the effective index profiles along the longitudinal direction of the vertical coupler for both TE and TM polarizations. The various regions and design parameters are identified.

3.2.4 Examples of Polarization-Independent Vertical Coupler Design

We present two sample designs of polarization-independent vertical couplers: (i) as input stage of a passive actual device, and (ii) as input stage of an active actual device. For the first design, the top waveguide core is assumed to have a refractive index of 3.32 (for a passive InGaAsP material with bandgap wavelength, $\lambda_g \approx 1.2 \mu\text{m}$) and thickness of $0.70 \mu\text{m}$. The passive actual device is assumed to be $3.0 \mu\text{m}$ in width. The critical width is $1.85 \mu\text{m}$ and the corresponding effective index is 3.235. In order to match the critical width and resonant widths, the underlying waveguide core is designed to have a refractive index of 3.25. The effective index curves are shown in Fig. 3.7(a). The transfer region (taper) is tapered from $1.40\text{-}2.00 \mu\text{m}$ over a transfer length of $150 \mu\text{m}$ after optimization.

For the second design, the top waveguide core has a refractive index of 3.5 (for an active material with $\lambda_g \approx 1.5 \mu\text{m}$) and thickness of $0.60 \mu\text{m}$. The active actual

device is assumed to be $2\ \mu\text{m}$ in width. In this case, the critical width is about $1.20\ \mu\text{m}$ and the corresponding effective index is 3.36, as presented in Fig. 3.7(b). To match the critical width with the resonant widths, the underlying waveguide is designed to have a refractive index of 3.36, and the transfer region is tapered from $1.10\text{--}1.20\ \mu\text{m}$ over a transfer length of $150\ \mu\text{m}$. The smaller width differential (difference between final width and initial width) for the active device design, as compared to the passive device design, is due to the steeper dispersion curve over taper width, which requires flatter taper to ensure a longer phase matching region. A sufficiently long phase matching region is needed to obtain higher light transfer efficiency. For all cases, the spacer thickness is set as $0.2\ \mu\text{m}$, which is found to be the optimum thickness for vertical coupling. For all simulations, the input fields are assumed to be the fundamental guided mode of the underlying waveguide, and the transfer efficiency is calculated by overlapping the local propagating mode with the fundamental mode of top waveguide. 3-D Finite Difference Beam Propagation Method (FDBPM) is used [113-114].

Fig. 3.7. Effective index of the individual waveguide at various taper widths for the case of (a) passive top waveguide, and (b) active top waveguide. n —refractive index.

The simulation results for these two designs are shown in Fig. 3.8. The transfer efficiencies for both cases are found to be greater than 90% on average. The small discrepancy in transfer efficiency between the polarizations is due to the residual

Chapter 3 Design of Vertical Couplers for Polarization-Independent Coupling & Polarization Splitting

birefringence accumulated over the transfer region. Note that the TM polarization couples more strongly upward as it has a greater coupling coefficient (i.e., κ , which is related to the overlapping between the modes of the interacting waveguides) than the TE polarization. The rapid taper over the second buffer region also helps to attract more residual light from the spacer layer by rapidly increasing the effective index of the top waveguide. The minor power oscillations at the actual device region are due to mode beating between the top waveguide and the underlying waveguide that are still weakly coupled because of the finite difference in their effective index.

Fig. 3.8. Simulated power distribution between the top and underlying waveguides for the design with (a) passive actual device, and (b) active actual device, along with their mode contour plots (c) and (d), respectively.

As mentioned before, the vertical coupler is commonly used as a spot-size-converter. In Fig. 3.9, we show the spot-size conversion throughout the vertical light coupling for one of the design examples, which is the case with a passive actual device. The figures show the cross sections of the waveguide modes at different longitudinal distance, with the color contours represent the intensity distribution. As seen, the spot-size of the input mode, which is about $4 \text{ (width)} \times 3 \text{ (height)} \mu\text{m}^2$, is being transformed to a final mode size that matched with the one of the actual device (about $3 \times 1.5 \mu\text{m}^2$).

Fig. 3.9. Transverse field profiles for the vertical coupler showing the mode size at various propagation (longitudinal) distances: (a) $Z=0 \mu\text{m}$, (b) $Z=50 \mu\text{m}$, (c) $Z=100 \mu\text{m}$, (d) $Z=150 \mu\text{m}$, (e) $Z=200 \mu\text{m}$, and (f) $Z=250 \mu\text{m}$, demonstrating the spot-size conversion capability of the vertical coupler.

3.3 Design of Polarization Splitter

3.3.1 Design Principle

The design of the polarization splitter vertical coupler is similar to that of the polarization-independent vertical coupler, except for the taper design. For the polarization-independent coupler, the principle is to minimize the difference between

the resonant widths of the two polarizations. Hence, making them as close as possible to the critical width is the only way in fulfilling this. Paradoxically, for the design of polarization splitter, the guideline is to maximize the difference between the resonant widths of the TE and TM polarizations, and this will make them farther away from the critical width. The taper waveguide is then designed to embrace only the resonant width of the desired polarization. In this way, we can ensure that the resonant coupling happens only to the desired polarization. Subsequently, optimization is done to maximize the transfer efficiency of the desired polarization while suppressing the unwanted polarization. The farther the resonant widths are from the critical width, the easier the design would be.

Depending on the relative refractive indices of the top and underlying waveguides, the resonant widths can occur to the right, or to the left of the critical width. In Fig. 3.10, the resonant widths are shown to be at the left of critical width. In the figure, the dotted curves show the effective index of the individual (uncoupled) waveguides, while the solid curves show the effective index of the supermodes, for TE and TM polarizations, as the taper width increases (supermodes—guided modes of the whole structure). The top waveguide is assumed to have a core refractive index of 3.55 and core thickness of 0.55 μm . The underlying waveguide is assumed to have a core refractive index of 3.27. The effective index of the supermodes can be used as an indicator for the location of the propagating mode. When the effective index converges to that of the top waveguide, it indicates that the light has been transferred up to the top waveguide.

Note that there exists a region near the first resonant width (i.e., TM resonant width) where one of the polarizations has started its light transfer, while there is no light transfer for the other polarization. It is found that the farther the resonant widths are from the critical width and the steeper the effective index curves are, the wider this region will be. The wider the region, the easier the design effort as the transfer

activity for each polarization can be clearly distinguished. The taper waveguide will then be designed to embrace the resonant width of the preferred polarization only. For example, for a TM-preferred vertical coupler (or TE-filter), the taper should begin at some width smaller than the TM resonant width, but stop short of the TE resonant width, and vice versa for TM-filter.

Fig. 3.10. Effective indexes as a function of the taper widths for the confined TE and TM supermodes (solid curves) of the vertical coupler and the individual uncoupled waveguides (dotted curves).

3.3.2 Example of Polarization Splitter Design

We look at an example of polarization splitter using vertical coupler, where it is used as input stage of an active device. The design corresponds to the case illustrated in Fig. 3.10. The underlying waveguide has the same geometry as those in the polarization-independent vertical coupler. For this design, the top waveguide core has a material index of 3.5 (i.e., active device) and the core thickness is $0.55 \mu\text{m}$, and the critical width is about $1.17 \mu\text{m}$. The spacer thickness is fixed at $0.2 \mu\text{m}$. For the lower waveguide the optimum material index is found to be 3.27 corresponding to an effective index of 3.256. The TM and TE resonant widths are about $0.69 \mu\text{m}$ and $0.78 \mu\text{m}$ respectively. As mentioned before, the taper waveguide initial and final widths are designed to embrace the resonant width of the desired polarization, but to stop short

of the resonant width for the unwanted polarization. Hence, for the TM-preferred splitter (TE-filter), the transfer region is tapered from $0.63\ \mu\text{m}$ to $0.69\ \mu\text{m}$, while for the TE-preferred vertical coupler (TM-filter), the transfer region is tapered from $0.73\ \mu\text{m}$ to $0.78\ \mu\text{m}$. All taper lengths are $200\ \mu\text{m}$, and the active device waveguide is assumed to be $2\ \mu\text{m}$ wide.

Fig. 3.11 shows the simulation results for the TE and TM polarization splitters. For the TM-preferred vertical coupler, the transfer efficiencies for TM and TE are about 95% (excess loss of 0.22dB) and 1%, respectively. For the TE-preferred, the transfer efficiencies for TE and TM are about 90% (excess loss of 0.45 dB) and 1%, respectively. Both designs have contrast ratios of around 19 dB. Hence, TE- and TM-filters with very high contrast ratios and minimal transfer loss are obtained. This is comparable to other polarization splitters in the literature [59-66].

Fig. 3.11. (a) Transfer efficiencies to the top waveguide for the TM-preferred vertical coupler and TE-preferred vertical coupler, with their contour plots in (b) and (c), respectively

The design of the case where the resonant widths are to the right of the critical width tends to have poorer performance (i.e., smaller contrast ratio). This is due to the smaller slope of the dispersion curves, which causes the light transfer of both polarizations to occur almost concurrently and difficult to be distinguished. The only advantage of this region is that the resonant widths are somewhat larger and the taper is easier to fabricate.

3.4 Other Applications and Considerations

3.4.1 Fabrication Tolerance

In the actual fabrication, the device property may deviate from the designed value. Hence, it is important to investigate the performance of the vertical coupler under these circumstances, and the results could serve to predict the possibility of real fabrication.

The spacer layer ensures that the upper waveguide mode is better confined and spatially well separated from the lower waveguide, but it reduces the coupling. The thicker the layer, the smaller the modes overlap, and hence the lesser the light coupling. Nevertheless, too thin the spacer thickness will introduce more power leakage to the bottom waveguide, which impairs the transfer efficiency. Hence, in our simulations, the optimum thickness is found to be 0.2 μm .

In practice, the spacer thickness could vary. In Fig. 3.12, the performance of the device is evaluated for different spacer thicknesses. For case study, the design example of the all-passive polarization-independent VC is used (i.e., top waveguide core thickness of 0.70 μm and material index of 3.32, and underlying waveguide core material index of 3.25). It is found that the transfer efficiency still remains reasonable ($\geq 80\%$) for up to ± 0.10 μm of deviation, which is able to be controlled by the current

epitaxy layer growth technologies. The TM polarization is more sensitive to the decrease of spacer thickness because the propagation mode field spreads wider in vertical direction, which causes higher power leakage to the underlying waveguide. On the other hand, the TE coupling is more sensitive to the increment in spacer thickness. This is because for the TE propagation mode that is more laterally wide-spread, the modes overlap is reduced significantly even for a small increment in the spacer thickness.

Fig. 3.12. Transfer efficiency to the top waveguide for various spacer thicknesses.

Given the optimum spacer thickness, the next important parameters are the initial width, final width and the transfer length that make up the transfer region. Fig. 3.13(a) and (b) shows the effect of varying the initial width and final width, respectively, on the transfer efficiency to the top waveguide while keeping other parameters constant.

Fig. 3.13. Transfer efficiencies for deviation in (a) initial width, and (b) final width from their original values of 1.40 μm and 2.00 μm, respectively.

As shown in Fig. 3.13, the polarization-independent vertical coupler is able to perform reasonably for deviation up to $\pm 0.10 \mu\text{m}$ of the initial width and final width. This imposes a rather strict requirement on the fabrication of the taper waveguide. Hence, optimization on the fabrication process would be needed in getting the desired dimensions.

Besides the taper widths, the transfer length will also affect the performance of the coupler. Fig. 3.14 presents the transfer efficiencies for various taper lengths. It is found that for taper length more than $150 \mu\text{m}$, the transfer efficiencies are almost insensitive to the transfer length. This also explained our selection of $150 \mu\text{m}$ as the taper length to achieve greater compactness in our designs. On the other hand, for smaller length, the transfer efficiency deteriorated drastically. This is because steep taper velocity allows smaller phase matching window. Thus, we can see that the vertical coupler has large tolerance at longer transfer length ($\geq 150 \mu\text{m}$), and in real fabrication, a slightly longer transfer length may be used in order to offset the small tolerance at shorter taper length ($< 150 \mu\text{m}$).

Fig. 3.14. Transfer efficiency to top waveguide for various transfer/taper lengths, with the initial width and final width remain unchanged at $1.40 \mu\text{m}$ and $2.00 \mu\text{m}$, respectively.

It is also found that long transfer length will relax the strict requirement on the refractive index of the top waveguide core. Although the use of taper provides a more robust design than the one without taper, the operation of VC in general still requires an accurate knowledge of the exact refractive index values of the waveguides. In particular, the resonant width and the critical width are quite sensitive to the change in the top waveguide core index. Deviation from the optimum refractive index will shift the dispersion curves, which in turn may shift the resonant width out of the transfer region, thereby degrade the transfer efficiency. In general, the smaller the taper velocity, which describes the speed of taper expansion, and the larger the differential width, which is the difference between the initial and final taper widths, the larger the tolerable index change for the top waveguide core and the more robust the taper design will be.

In Fig. 3.15, we show the effect of lengthening the transfer region on the tolerable refractive index deviation for the polarization-independent vertical coupler. For the case discussed earlier, where the initial and final widths are 1.4 μm and 2.0 μm , respectively, and the taper length is 150 μm , the maximum index deviation corresponding to a transfer efficiency of 70% (or a transfer loss of 1.5 dB) is only 0.008 (or $\pm 0.2\%$ change of the refractive index). If we increase the taper length while maintaining the same taper velocity, the maximum index tolerance increases to 0.01 at taper length of 450 μm (the initial width is changed to 0.2 μm to maintain the same taper velocity). If the taper velocity is allowed to decay by increasing the length to 1000 μm , the index tolerance is further increased to 0.04. Note that the index tolerance is not symmetric: the transfer efficiency is more tolerant to positive change in the core index. This is because higher top waveguide core index will assist in attracting the propagation mode to the top waveguide. In our previous sample designs, we have traded some robustness for compactness. The optimum length would in practice be decided by a compromise between these two considerations.

Fig. 3.15. Transfer efficiencies as a function of deviations in the upper waveguide core index for various taper velocities or taper differential widths.

In terms of operating wavelength variations, both polarization-independent coupler and polarization mode splitter are able to provide reasonable performance as long as it only deviates within ± 10 nm. For the case where the taper differential width is large, such as for the all-passive polarization-independent VC, the tolerance could be as high as ± 50 nm, as shown in Fig. 3.16. This relatively broadband performance is because the effective indexes of the vertical coupler are relatively insensitive to the change of operating wavelength.

Fig. 3.16. Transfer efficiency against different deviations of operating wavelength. The optimum operating wavelength is assumed to be $1.55 \mu\text{m}$.

3.4.2 Multimode Characteristic

In our simulations so far, we have assumed that the input light consists of only the fundamental mode of the lower waveguide to ease the analyzing of results. Practically, since the lower ridge waveguide in our vertical coupler has a large cross section, it is expected that the waveguide is multimode. The higher order mode could be excited by the fiber misalignment or the rough waveguide surface after long propagation distance. In order to be single mode for our underlying waveguide, which has a cross section of $4 \times 3 \mu\text{m}$, the refractive index of the waveguide core has to be within 0.8% of the cladding index. This corresponds to about 3.195 with respect to the cladding refractive index that is 3.17 for InP. For our designs, however, in order to match the desired resonant width, the underlying waveguide is not likely to have such a small refractive index. Consequently, the underlying waveguide could be multimode. Therefore, it is important to investigate the behavior of the vertical coupler given that the input mode is not the fundamental mode.

As a case study, one of the sample designs of the previous subsection on polarization-independent vertical coupler is used, where the underlying waveguide has a core index of 3.36, and the upper waveguide core has a material index of 3.50 and thickness of $0.6 \mu\text{m}$. For this design, the underlying waveguide can support higher order modes. However, since the fractional power for a particular mode decreases as the mode order increases, we need only to look at the few lowest order modes. The intensity profile of the four lowest orders of TE polarization (including the fundamental mode) for the underlying waveguide are shown in the insets of Fig. 3.17. For the TM polarization, the profiles are similar and the effective indexes are only slightly different since the underlying waveguide is relatively symmetric in the cross section. In order to study the device behavior subjected to the excitation of different mode orders, each of the guided modes is launched into the underlying waveguide separately and the transfer efficiency to the top waveguide is observed. The transfer

efficiencies are plotted against the mode order in Fig. 3.17. It was found that for higher order modes, the transfer efficiencies reduce and eventually become zero. The first order mode has the highest transfer efficiency among all the higher order modes, but it is only about 20%. The reduction of transfer efficiency is because the resonant widths of higher order modes are larger than the one of fundamental mode, and hence, they are usually excluded from the transfer region.

Fig. 3.17. Simulated transfer efficiencies for the different mode order of the underlying waveguide, for both TE and TM polarizations. For illustration, the insets show the corresponding mode intensity profiles for TE polarization.

From the result, we can see that the potential perturbation from the higher order modes are insignificant compared to the fundamental mode. Since in a multimode waveguide, the fundamental mode is usually dominant, whereby the fractional power for the higher order modes are much lower, we can safely ignore the effect of the higher order modes on the performance of the vertical coupler.

3.4.3 Gaussian Mode Input

In the real application, the input to the vertical coupler may not have settled down to the fundamental mode of the underlying waveguide when the light transfer occurs.

Hence, in order to access the performance of the vertical coupler under this condition, a fiber mode input (Gaussian approximation) is injected into the vertical coupler. The mode radius is assumed to be $5\text{ }\mu\text{m}$, which is the mode radius for a standard single mode fiber. The example used corresponds to the polarization-independent vertical coupler with passive device. The simulation result for the representative TE polarization is shown in Fig. 3.18. In the figure, we can estimate that the fiber coupling loss is about 3.7 dB from the initial power at the bottom waveguide. The transfer efficiency to the top waveguide is about 95% (excess loss of about 0.2 dB). This gives us a total insertion loss of about 3.9 dB. More importantly, the result shows that even under the fiber mode input, the vertical coupler is still able to transfer the light with very high efficiency. The fluctuation at the top waveguide will eventually settle down after a longer distance of propagation.

Fig. 3.18. Power distribution along the propagation distance for a standard SMF mode input (Gaussian approximation) with TE polarization.

3.4.4 Three-Layer Vertical Coupler

The vertical coupling is a powerful concept that can be generalized to more than two waveguide layers. For example, one can imagine a three-waveguide structure, where the top upper waveguides may be an active device, the middle waveguide is a passive device, and the bottom waveguide is a passive coupling device. The

advantage of this vertically integrated structure is not only to minimize the coupling loss, but also to enable different material structures required for the active and passive devices to be optimized independently and grown in a single-step growth, rather than by regrowth as in the case of planar integration.

The 3-layer VC structure is illustrated in the inset of Fig. 3.19 and summarized in Table 3.1. Note that an average transfer efficiency of 80% is achievable. However, because of the close proximity between the waveguide effective indices, the power oscillations are much stronger and the two upper waveguide modes are also not very well separated. Nevertheless, this represents the first simulated demonstration of 3-layer vertical coupler.

Fig. 3.19. Relative power distribution along the propagation distance for TE mode. TM mode is similar. The inset shows the schematic of the cross section for the three-level vertical coupler. WG—waveguide

Chapter 3 Design of Vertical Couplers for Polarization-Independent Coupling & Polarization Splitting

Table 3.1: Design parameters for the 3-layer vertical coupler.

Design Parameter	Value
Lower core index	3.29
Lower core cross sectional area	$4 \times 3 \mu\text{m}$
Lower spacer thickness (between lower waveguide and middle waveguide)	$0.2 \mu\text{m}$
Middle core index	3.43
Middle core thickness	$0.6 \mu\text{m}$
Middle taper waveguide (initial width, final width, and taper length)	1.0, 1.25, $150 (\mu\text{m})$
Upper core index	3.50 (active)
Upper spacer thickness (between middle waveguide and top waveguide)	$0.4 \mu\text{m}$
Upper core thickness	$0.5 \mu\text{m}$
Upper taper waveguide (initial width, final width, and taper length)	1.0, 1.6, $150 (\mu\text{m})$
Top cladding thickness	$1 \mu\text{m}$

3.5 Design of Single-Mesa Vertical Coupler

Most vertical couplers found in the literature are based on the double mesa structure. Double mesa structure is preferable as it is able to provide better mode confinement for the underlying waveguide and the top waveguide. As a part of the research work, we would like to show that a vertical coupler could be constructed just by having a single-mesa structure. Potentially, it could reduce the fabrication steps of the vertical coupler. The conventional fabrication process of double-mesa vertical couplers is relatively more complicated. The double mesa requires at least two photolithography and etching steps and results in a non-planar structure. Planarization and etch-back (e.g., using BCB) are usually required to ease the critical alignment of the upper waveguide with respect to the lower mesa. Also, the light transfer is highly sensitive to fabrication deviations, and thus all the processes must be controlled stringently. Therefore, it is always desirable to minimize the number of process steps.

The single-mesa vertical coupler is based on an underlying rib waveguide and a top ridge waveguide. The underlying waveguide consists of a slab material, in which the weak lateral guiding is given by the loading effect by the top ridge waveguide. Hence, no further fabrication steps are required to define the underlying waveguide, and the critical alignment between two vertically stacked waveguides can be avoided. To better illustrate this, Fig. 3.20 shows a comparison between the conventional double-mesa VC process and the single-mesa VC process, where we can clearly see that the steps needed for single-mesa VC are much less than the double-mesa VC.

Fig. 3.20. Comparison between the conventional double-mesa vertical coupler process and the single-mesa vertical coupler process.

The larger, weakly guiding underlying waveguide acts as the input coupling waveguide while the actual device is at the top waveguide. The two waveguides are separated by a spacer layer. The schematic of the vertical coupler is shown in Fig. 3.21. The top waveguide begins with a uniform section, which provides the loading effect for the bottom input waveguide, followed by a linear taper section that acts as the light transfer region to the actual device. After that, it is up-tapered for a distance of 30 μm to the width of the actual device. The structure is similar to the double mesa

VC, except that the transfer region begins with a uniform section, and there is no steep taper region before the transfer region.

Fig. 3.21. Schematic of single-mesa vertical coupler

The actual device material structure is assumed to be pre-determined by application. In our example, the device waveguide core is assumed to have a material index of 3.50, a thickness of $0.6\ \mu\text{m}$, and a width of $2\ \mu\text{m}$, while the underlying waveguide core is assumed to have an index of 3.42, and the spacer, claddings and substrate are all assumed to be InP with an index of 3.17. The remaining variable parameters are the lower waveguide core thickness, the spacer thickness, the taper waveguide initial and final taper widths, and the taper length. For the fiber coupling consideration, we assume a standard single-mode fiber with a mode-field diameter of $10\ \mu\text{m}$.

In the design of a single-mesa vertical coupler, the fiber coupling efficiency to the input waveguide is one of the considerations. For this, the input waveguide mode plays an important role. The design of the input waveguide is relatively more complicated than the double-mesa VC, as the bottom waveguide mode is not only dependent on its own geometry and material, but also is dependent on the loading effect from the top waveguide. The thickness of the bottom waveguide core is one of the factors that decide the input mode profile, which in turn affects the fiber coupling. Fig. 3.22(a) shows the simulated fiber coupling loss for the different core thickness

under various spacer thicknesses. TE polarization will be used as a representative study in this subsection. It is found that the thinner the bottom waveguide core, the stronger the loading effect due to the top ridge waveguide. Hence, the confined mode will become more symmetric, which is favorable for better fiber coupling. There exists an optimum core thickness, at which the loss is minimized. As the thickness is further reduced, the fiber coupling loss increases drastically due to the shift of eigenmode to the top ridge waveguide. For the spacer thickness of $0.3\ \mu\text{m}$, it is found that the optimum core thickness is $0.7\ \mu\text{m}$, which gives a coupling loss of 6.5 dB. This is an improvement of 8.5 dB as compared to the direct coupling to the top waveguide.

Fig. 3.22. Simulated fiber coupling loss to the single-mesa vertical coupler for: (a) various bottom core thicknesses at different spacer thickness, (b) different spacer thickness at the optimum bottom core thickness, and (c) different top waveguide width at different spacer thickness.

The spacer thickness is chosen such that the overall device height is reduced (for stronger light transfer and easier epitaxy growth), while maintaining reasonable separation between the two waveguide modes. The thicker the spacer, the weaker the lateral light confinement at the underlying waveguide as the loading effect is weaker. This will reduce the fiber coupling as the waveguide mode becomes more asymmetric. Furthermore, the transfer efficiency suffers because the centroids of the two waveguide modes are further apart. On the other hand, if the spacer is too thin, it will cause more back coupling from the actual device region to the underlying waveguide. Fig. 3.22(b) shows the fiber coupling loss for different spacer thicknesses at the bottom core thickness of $0.7\ \mu\text{m}$, where it can be seen that at $0.3\ \mu\text{m}$, the loss is minimum.

The loading effect for the bottom rib waveguide is supplied by the uniform section of the top waveguide. The waveguide width must not be too wide to shift the guiding mode to the upper waveguide or too narrow to made fabrication difficult. Fig. 3.22(c) presents the fiber coupling loss for different top waveguide widths, under various spacer thicknesses. The bottom core thickness is assumed to be $0.7\ \mu\text{m}$. With the optimum spacer thickness of $0.3\ \mu\text{m}$ and bottom core thickness of $0.7\ \mu\text{m}$, $1\ \mu\text{m}$ is found to be the optimum width that gives the lowest coupling loss.

As similar to the double-mesa vertical coupler, a single-mesa vertical coupler also transfers the light through resonant coupling at the resonant width. Fig. 3.23 shows the effective indices of the underlying rib waveguide and the top waveguide when the top waveguide width is varied along the taper. The effective indices are polarization dependent due to the asymmetric waveguide structure; hence, there are two resonant widths, one for TE polarization and another for TM polarization. Note that the effective indexes of the top waveguide mode also intersect at a point, and the corresponding waveguide width is the critical width, W_c . If the resonant widths are close to W_c , then the polarization dependence in transfer efficiency is negligible. Here, we would like

our vertical coupler to be polarization independent; hence, in the design of Fig. 3.23, the critical width, TE and TM resonant widths are designed to be close to each other, which is around $1.2 \mu\text{m}$.

Fig. 3.23. Effective index curves of the single-mesa vertical coupler. The top waveguide core has a refractive index of 3.50, while the bottom waveguide has a refractive index of 3.42.

With the initial taper width fixed at $1 \mu\text{m}$ for the reasons given in the previous subsection, the final width of the transfer region is varied to maximize the transfer efficiency. Two taper lengths (or transfer lengths) are investigated, i.e., $150 \mu\text{m}$ and $400 \mu\text{m}$. The transfer efficiency as a function of the final taper width is shown in Fig. 3.24. From the figure, it can be seen that at the final taper width of $1.3 \mu\text{m}$, the transfer efficiencies for both polarizations are maximized. This width, together with the initial taper width, encompasses the resonant widths and the critical width of around $1.2 \mu\text{m}$. For a taper length of $150 \mu\text{m}$, the transfer efficiencies for TE and TM polarizations are found to be 91% and 92%, respectively, giving a polarization-dependent loss of only 0.047 dB. The sensitivity to taper width can also be deduced from this figure. For instance, the transfer efficiencies for TE polarization are still above 80% within $\pm 0.1 \mu\text{m}$ deviations from the optimum final width. The transfer efficiency is higher and less sensitive to the final width for larger taper length, also

shown in Fig. 3.24. This could be due to the adiabatic coupling that occurs in a longer transfer region. Nevertheless, to achieve a more compact device and smaller polarization-dependent loss, the transfer length of 150 μm is chosen in our design.

Fig. 3.24. Transfer efficiency of the single-mesa vertical coupler for various final taper widths at the transfer lengths of 150 μm and 400 μm .

The FDBPM simulation results for the above optimized results are shown in Fig. 3.25. At the initial region, the overlap integral with the eigenmode of the top waveguide is not zero because the bottom rib waveguide mode field extended slightly into the top waveguide. It can be seen that the TM polarization couples more strongly and rapidly to the upper waveguide than the TE polarization. In the rapid taper between the transfer region and the actual device, the rapid increase in the effective index helps to attract more residual light from the spacer layer into the upper waveguide. In the actual device region, some back-coupling is observed because of the mode beating between the two weakly coupled waveguides.

Fig. 3.25. (a) Contour plot showing the light transfer, and (b) transfer efficiency, to the top waveguide, for TE and TM polarizations along the propagation distance.

Chapter Summary

In this chapter, we have designed polarization-independent vertical coupler and polarization splitter based on asymmetric ridge HIC waveguides. The polarization-independent vertical coupler is able to provide transfer efficiency of around 90% for both TE and TM polarizations. For the polarization splitter, the contrast ratio of around 19 dB is achieved. The capability of the vertical coupler in polarization control has expanded its application to not just being used for improving the fiber coupling and 3-D integration. To reduce the complication in the fabrication of double-mesa vertical coupler, a single-mesa vertical coupler is also proposed. The fabrication process is much simpler, where only a single flow of lithography and etching is needed. No critical alignment of the top and underlying waveguides is needed. The vertical coupler is also able to transfer the light polarization-independently.

Chapter 3 Design of Vertical Couplers for Polarization-Independent Coupling & Polarization Splitting

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Author's Related Publications

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1. M.-K. Chin, C.-W. Lee, J. Shen, "Polarization-independent vertical coupler for photonics integration," *Optics Express*, vol. 12, pp. 117-123, 2004.
2. C.-W. Lee, M.-K. Chin, "Design of vertical polarization mode splitter with mode-size transformer," *Photonics Technology Letters*, vol. 16, pp. 2069-2071, 2004.
3. C.-W. Lee, M. K. Chin, M. K. Iyer, and A. Popov, "Asymmetric waveguides vertical couplers for polarization-independent coupling and polarization-mode splitting," *J. Lightwave Technol.* vol. 23, No. 4, pp. 1818-1827, Apr. 2005.
4. C.-W. Lee, M. K. Chin, "Design of polarization filter based on vertical coupler," in *Integrated Photonics Research and Applications (IPRA)*, San Francisco, U.S.A., pap. IFC4, June 30-July 2, 2004.
5. C.-W. Lee, M.-K. Chin, "Vertical coupler architecture for polarization-independent coupling and polarization-selective coupling," *Photonics Asia*, Beijing, China, Oct 8-12, 2004.
6. C.-W. Lee, S.-Y. Lee, M.-K. Chin, "Design of a Single Mesa Vertical Coupler," *Photonics North'06*, Quebec City, Canada, pap. GW-05-4-3, June 5-8, 2006.

4

Design of Lateral Mode Filter

In this chapter, we present another device from the filter category that can potentially be integrated with other photonic devices. The device is a lateral mode filter, which can be used to filter out the higher order waveguide modes that are excited in a high-index-contrast waveguide. The design principle is simple and robust, and can be applied to any ridge waveguide device, irrespective of the waveguides cross section, material system and operating wavelength.

4.1 Design Structure and Principle

4.1.1 Waveguide Mode in High-Index-Contrast (HIC) Waveguide

A mode is a solution of the Maxwell's equations for a particular waveguide. It represents the transverse field profile of the electric and magnetic fields that propagate unchanged along the waveguide. A mode usually has a sinusoidal amplitude profile within the waveguide core, and penetrates into the cladding region in exponential decay fashion (i.e., evanescent wave). Each mode propagates in the waveguide with a unique propagation constant, defined as $\beta = (2\pi/\lambda)n_{\text{eff}}$, where n_{eff} is the effective index; the higher mode order has smaller propagation constant or effective index. The number of supported modes in a waveguide depends on many factors, including the material index contrast between the core and the cladding, and the dimensions of the waveguide core.

An InP-based ridge waveguide is considered a high-index-contrast (HIC) waveguide because the index ratio between the core (InP compound semiconductor) and the cladding (air) in the lateral direction is larger than 3:1. This high index difference means that the light is strongly confined in the waveguide laterally, which enables waveguide bending with very small radius. However, an HIC waveguide is easily multimode. To be single-mode, the waveguide has to be as narrow as hundreds of nanometer in width. Fig. 4.1 shows an example of the simulated effective indexes for all the modes in an HIC waveguide as a function of width. The mode intensity profiles and the waveguide parameters are presented in the insets. Only the few lowest order modes are shown. It can be seen that for the particular waveguide structure shown (where the core thickness is 0.65 μm): (i) the single mode waveguide is less than 900 nm in width (this critical width depends on the core thickness and the index difference in the vertical direction); (ii) the wider the waveguide (assuming other parameters unchanged), the more modes are supported; (iii) the higher the mode

order, the smaller the effective index, which also represent the propagation constant;
 (iv) the higher the mode order, the number of intensity peaks increases.

Fig. 4.1. Effective index of a representative InP-based HIC waveguide at different widths for TE and TM polarizations. Insets show the mode intensity profiles and the waveguide cross section.

4.1.2 Application of Mode Filter

As mentioned previously, some photonic devices require single-mode waveguides. As an example here, we shall look at the effect of higher order mode input on the performance of a cross-coupled directional coupler. The directional coupler consists of two 1.5 μm wide waveguides separated by a gap of 0.1 μm . The core index is assumed to be 3.42 ($\lambda_g \approx 1.4 \mu\text{m}$) and the core thickness is 0.7 μm . For a directional coupler, the coupling length, L_c could be calculated by using

$$L_c = \frac{\lambda_o}{2(n_e - n_o)} \quad (4.1)$$

where n_e and n_o are the effective indexes for the even and odd supermodes of the coupled waveguide. For the fundamental mode, L_c is found to be about 742 μm ($n_e=3.309692$ and $n_o=3.308647$), while for the first order mode, L_c is about 160 μm ($n_e=3.194512$ and $n_o=3.189671$). Fig. 4.2 shows the simulation results that illustrate

the coupling length in the 3-D waveguides. The relatively fast power oscillation for the first order mode will cause uncertainty at the output, in which a small discrepancy in the device length could have significant different output power. The output power will also be affected by the fractional power of the first order mode excited, and this is hard to control. Therefore, it is always desired to have only the fundamental mode in the waveguide. With an additional mode filter at the device input, this problem could be solved.

Fig. 4.2. Normalized waveguide powers along the propagation distance for the directional coupler when the input is the fundamental mode and first order mode.

4.1.3 Design Structure and Principle of Higher Order Mode Filtering

The mode filter consists of a single-mode waveguide, sandwiched by two taper waveguides, as shown in Fig. 4.3. The front taper waveguide has an initial width that is predetermined by the input multimode waveguide, and a final width matched with the single-mode waveguide. At the latter section, a similar taper waveguide interfaces the single mode waveguide with the output waveguide, which could be identical or be different from the input waveguide. Vertically, the thickness and refractive indices of various layers are the same as the input waveguide, which demonstrated the versatility of the structure.

Fig. 4.3. Schematic of the higher order guided modes filter (not drawn to scale).

In the input multimode waveguide, the propagating field is in general given by a summation of modes: $\psi(x, y, z) = \sum_v a_v U_v(x, y) e^{j\beta_v z}$, where U_v is called the v th eigenmode field of the waveguide, β_v the corresponding propagation constant, and a_v the excitation amplitude. In the effective index approximation, the 3-D down-taper waveguide structure can be considered as a slab waveguide with varying thickness. Applying the local normal mode approximation [115] to a 2-D tapered structure, one can define the local propagation constant for each mode by [116]

$$\beta_v(z) \approx k_o n_r - \frac{\pi \lambda_o}{4 n_r} \left[\frac{v+1}{W_e(z)} \right]^2 \quad (4.1)$$

where n_r is the ridge effective index, v is the mode order and W_e is the modal effective width. Due to the strong lateral confinement of HIC waveguide, we can assume that W_e is almost the same as the local waveguide width. From the equation, we can see that as the width reduces and the mode order increases, the propagation constant reduces. The smaller propagation constant implies that the light confinement is weaker. Hence, we can imagine that as a multimode input light propagates into a down-taper waveguide, where the width is decaying with z , the propagation constant for all modes will reduce, and it is particularly severe for the higher order guided modes since they usually have much smaller effective indexes than the fundamental mode. Furthermore, larger mode order also increases the $v+1$ term significantly. Hence, the higher order modes will be easily dissipated as leaky mode when the

taper width reaches a cut-off width (i.e., when their propagation constants are less than that of the cladding). In the 3-D scenario, these modes will tunnel into the substrate as leaky modes. This forms our mechanism—mode discrimination, in filtering off the higher order mode while preserving the fundamental mode in the waveguide.

When the first-order mode reaches cut-off the input taper is terminated and followed by a uniform single-mode waveguide section, in which complete attenuation of the higher order modes occurs leaving only the fundamental mode. After this, an up-taper waveguide (or a mode size transformer) is used to restore the fundamental mode to the original mode size without re-exciting the higher-order modes. The design of the taper filter consists of determining the most compact optimum dimensions for each of these sections. The mechanism discussed above remains valid irrespective of the light polarizations (i.e., TE or TM). In a 3-D waveguide structure, varying the width represent a more feasible and easier choice in achieving the cut-off limit, despite that the other waveguide parameters could be varied as well. However, the cut-off width could not be obtained easily, whereby the assistance of simulation software is needed.

4.2 Example of Design and Discussions

We simulated the propagation loss of various modes, at the operating wavelength of 1.55 μm , in a complete structure based on the InP-InGaAsP material system. We consider an input multimode ridge waveguide having a core index of 3.42, a core thickness of 0.5 μm , and a width of 3 μm . The top cladding (InP) layer thickness is assumed to be 1.5 μm with an index of 3.17, and the lower cladding and substrate are both InP. This waveguide structure supports four lateral modes. The transverse TE

intensity profiles of the multiple modes are shown in the Fig. 4.4. The mode profiles of TM polarization are similar, just that the effective indexes are different.

Fig. 4.4. Transverse intensity profiles of the multimode HIC input waveguide, with the different colors represent the intensity distribution.

For the initial simulations the single mode waveguide and the input and output taper waveguides are all 30 μm long, such that the taper slope (about 2.6°) is small enough that radiation and back-reflection losses may be neglected [57], and one-directional BPM simulation is approximately valid. To clearly observe the behavior of each mode through the mode filter, the individual modes are launched into the filter separately. Fig. 4.5(a)-(d) show the lateral mode profiles for all four modes ($v=0, 1, 2, 3$) as they propagate through the whole device. The results for TE polarization are presented as representative study. It can be seen that all the higher-order modes are strongly attenuated at the output. In the case of the $v=2$ mode there is a trace of mode conversion to the fundamental mode due to the nonzero coupling coefficient between the $v=0$ and $v=2$ modes. For the fundamental mode, the loss is small, and

mode conversion to the second order mode at the output taper is negligible (the highest is 0.3% for TM polarization), as calculated by taking the overlap of the output field with the second-order mode. The original shape of the fundamental mode is fully recovered at the output. Fig. 4.5(e) displays the vertical contour plot for the $v=2$ mode, which is meant to show the substrate leakage effect as the mechanism for suppressing the higher-order modes, as discussed earlier.

Fig. 4.5. Simulated lateral intensity profiles (X-Z) along the propagation distance when the input mode is (a) $v=0$ (fundamental mode), (b) $v=1$, (c) $v=2$, (d) $v=3$ (the monitor height is $1.75 \mu\text{m}$ from the top of the ridge, which coincides with the middle of the core layer), and (e) the vertical contour plot for $v=2$ in the Y-Z plane at the center of the waveguide, showing the substrate leakage loss that occurs mostly in the input taper and the single-mode waveguide. The ridge is $2 \mu\text{m}$ deep.

The filtering efficiency for higher-order modes is primarily dependent on three inter-related parameters, i.e., the width and the length of the single-mode waveguide,

and the length of the input taper. Let us first discuss the single-mode waveguide width. From the fabrication point of view, it is not desirable for the optimum width to be too small. To a large degree, the optimum width is related to the etch depth of the ridge waveguide and can be controlled accordingly. As an example, Fig. 4.6 shows, for two extreme values of the etch depth, $D_{etch} = 2$ and $4 \mu\text{m}$, the propagation losses in dB through the whole device for the fundamental and the first-order modes as a function of the single-mode waveguide width, assuming the input and output tapers and the single-mode waveguide to be all $30 \mu\text{m}$ long. Note that only the first higher order mode are shown. It represents the limiting case since the losses for other higher order modes are always higher in the single-mode waveguide section, where the total loss is mostly incurred. Also note that when the waveguides are narrow, the TE mode effective indices are smaller than the TM [117] (i.e., the TM modes are more confined), and hence the TE modes are more leaky.

Fig. 4.6. Calculated losses for the fundamental and first-order modes (both TE and TM) at the end of the output taper, for various single-mode waveguide widths, with an etch depth, D_{etch} of $2 \mu\text{m}$ (solid curves) and $4 \mu\text{m}$ (dotted curves). The simulated device consists of $30 \mu\text{m}$ input and output taper sections and a $30 \mu\text{m}$ single-mode waveguide section.

It can be seen that the differential loss is larger at the smaller etch depth for any given waveguide width. This is because the substrate leakage losses for the higher-order modes increase much faster with decreasing etch depth than those for the fundamental modes [118]. However, the etch depth must not be too small or the loss for the fundamental mode will also become too high. The optimum etch depth for any given single-mode waveguide width is that which gives the required differential loss (say, 20 dB) between the fundamental mode and the first-order mode ($v=1$) while keeping the loss for the fundamental mode below the acceptable limit. $D_{etch} = 4 \mu\text{m}$ (dotted curves) represents the deep-etch limit in which the substrate leakage effect is minimal. In this case a differential loss of 20 dB is achievable only when the waveguide width is down to about $0.25 \mu\text{m}$. On the other hand, $D_{etch} = 2 \mu\text{m}$ (solid curves) represents the shallow-etch limit in which the ridge is barely etched through the core layer and the presence of the substrate is fully felt. In this case the cut-off width can be as large as $0.8 \mu\text{m}$ for 20 dB differential loss and 0.02 dB loss for the fundamental mode. Finally, we note that the shallow etch profile will also suppress the higher-order modes in the input waveguide leading to the taper filter; thereby greatly increase the overall extinction ratio for the higher-order modes.

We will henceforth assume that the single-mode waveguide width is $0.8 \mu\text{m}$ and the etch depth is $2 \mu\text{m}$. In fact, this is the case assumed for the simulations in Fig. 4.5. This design will ensure sufficient suppression for all higher modes if the input taper and single-mode waveguide lengths are both $30 \mu\text{m}$ as shown earlier. We next consider the effect of varying the single-mode waveguide length, while keeping the other parameters fixed. The results are shown in Fig. 4.7 for two different input taper lengths, TL_i . The differential losses in dB due to substrate leakage are proportional to the length of the single-mode waveguide. On the other hand, losses for the fundamental modes are too small to be plotted. The differential losses for TM polarization are significantly smaller than those for TE, and thus the suppression of

TM polarization is more critical. The losses are only slightly different when the input taper length is increased from 5 μm to 30 μm . It can be seen that the minimum single-mode waveguide length needed to achieve 20 dB suppression of the TM polarization is about 25 to 35 μm for an input taper of 30 μm to ensure minimal distortion to the fundamental mode, as we will show later. Hence, in our design, 30 μm is used for the single-mode waveguide length.

Fig. 4.7. Calculated losses for the first order mode (both TE and TM) at the output of the filter as a function of the single-mode waveguide length. The width of the waveguide is assumed to be 0.8 μm . The etch depth is 2 μm and the input taper length is 5 μm and 30 μm , respectively. The output taper length is fixed at 30 μm .

So far, the input taper length, TL_i is mostly assumed to be 30 μm . As we have seen in Fig. 4.7, the input taper length does not significantly affect the higher-order mode suppression. On the other hand, a very small taper length ($< 30 \mu\text{m}$) can significantly increase the substrate leakage loss for the fundamental mode, due to the large perturbation on the propagating wave caused by the abrupt change in waveguide width. This is shown in Fig. 4.8, where the solid curves give the output powers for the fundamental TE and TM polarizations as a function of the input taper length (for a fixed output taper length). The output power is taken as the overlap

integral between the output field and the input fundamental mode. The overlap integral is less than one due to leakage loss in the fundamental mode and not due to mode conversion loss as discussed earlier. The general trend of increasing loss with decreasing taper length is consistent with FDTD simulations reported elsewhere [57].

Fig. 4.8. Calculated total losses for the fundamental TE and TM modes as a function of input taper length (solid curves), with the output taper length fixed at 30 μm ; and as a function of output taper length (dotted curves), with the input taper length fixed at 30 μm . The single-mode waveguide width is 0.8 μm and the length is 30 μm .

Since the taper waveguide is a low-loss linear device for the fundamental mode (assuming negligible mode conversion), reciprocity principle [119] dictates that the propagation of the fundamental mode should be identical in both forward and backward directions. This is indeed the case, as shown in Fig. 4.8, where the pair of dotted curves (one for TE and one for TM) giving the output powers as a function of the output taper length, TL_o (while keeping $TL_i = 30 \mu\text{m}$) are seen to overlap exactly with the pair of solid curves giving the output powers as a function of the input taper length, TL_i (with $TL_o = 30 \mu\text{m}$). Therefore, for the waveguide structure considered, an optimum and compact length of 30 μm can be used for both input and output taper waveguides. They, along with a single-mode waveguide length of 30 μm , make the whole filter a very compact and bi-directional device with a total length of only 90 μm .

Chapter Summary

In this chapter, the design of a mode filter using laterally tapered ridge waveguide is proposed. The mode filter comprises a down-taper waveguide and a single-mode waveguide for higher order modes discrimination, followed by a mode-size expander that restores the original fundamental mode size. The insertion loss for the fundamental mode could be as small as 0.02 dB. The operation is found to be insensitive to many of the device's dimensions. The versatile mode filter architecture is a building block that can be integrated to any ridge waveguide, irrespective of the waveguides cross section, material system and operating wavelength.

Author's Related Publications

1. M. K. Chin, C.-W. Lee, S. Y. Lee, S. Darmawan, "High Index Contrast Waveguides and Devices," *Applied Optics* vol. 44, No. 15, pp. 3077-3086, 2005.
2. C.-W. Lee, M.-K. Chin, "Design of lateral-modes filter based on high-index contrast waveguide," *Optics Communications*, vol. 253, pp. 87-94, 2005.
3. C.-W. Lee, M.-K. Chin, "Higher order lateral-modes discrimination in ridge waveguides for photonic integrated circuits," *Photonics Asia*, Beijing, China, Oct 8-12, 2004. (Invited paper)

5

Design of Polarization-Independent Coarse Wavelength Splitters based on Ridge Waveguide Conventional Directional Coupler

In this chapter, we will present the first unique design of a polarization-independent dual-wavelength splitter for wavelengths around 1.3 μm and 1.55 μm that is potentially of great interest to passive optical network (PON) applications. The filter design is simple compared with the other architectures, and is based on ridge-type lateral directional couplers that can be readily integrated with other planar waveguide devices. Two design examples, based on InP/InGaAsP and Si/SiGe waveguides, are given. This polarization-independent wavelength splitting is achieved by exploiting the polarization dependence of the waveguides to produce coupling lengths that are sensitive to polarization and wavelength. The same approach can be applied to the design of polarization splitter. The crosstalk, optical bandwidth and fabrication sensitivity for the wavelength filter are evaluated.

5.1 Design Principle

A conventional directional coupler (DC) consists of two identical waveguides, located side by side separated by a gap. It is the simplest waveguide structure that allows power transfer between two waveguides. An input into any of the two waveguides can be decomposed into two normal modes, one symmetric (even) and another asymmetric (odd). The profiles of the two modes are shown in Fig. 5.1. These two modes, which have different phase velocities, interfere with each other as they propagate along the directional coupler. The modes of the structure at any point will then depend on the outcome of the interference. As a result of the interference, the energy moves back and forth between these two waveguides in sinusoidal fashion. If the waveguides are lossless and symmetric, then the output powers in the bar and cross waveguides are given, respectively, by [121]

$$P_b = P_{in} \cos^2\left(\frac{\pi}{2} \cdot \frac{L}{L_c}\right), \quad P_c = P_{in} \sin^2\left(\frac{\pi}{2} \cdot \frac{L}{L_c}\right), \quad (5.1)$$

where P_{in} is the input power, L is the interaction length, and L_c is the coupling length, which is the distance for a complete power transfer (180° phase difference between the two normal modes). The coupling length is given by

$$L_c(\lambda, \varepsilon) = \frac{\pi}{\kappa} = \frac{\lambda}{2[n_e(\lambda, \varepsilon) - n_o(\lambda, \varepsilon)]} \equiv \frac{\lambda}{2\Delta n(\lambda, \varepsilon)}, \quad (5.2)$$

where κ is the coupling coefficient, and n_e and n_o are the effective indices of the even and odd modes, respectively. The coupling length is in general polarization (ε) and wavelength (λ) dependent.

Fig. 5.1 Amplitude profiles of the normal modes for the two waveguides in a conventional directional coupler

The periodic nature of the output power (as a function of distance) and the dependence of the coupling length on wavelength and polarization provide the mechanism for the DC to serve as a CWDM filter. This is because any two wavelengths, λ_1 and λ_2 , assuming $\lambda_2 > \lambda_1$, can be separated at the bar and cross ports if the interaction length L of the directional coupler satisfies the condition

$$L = mL_c(\lambda_1) = (m + p)L_c(\lambda_2), \quad (5.3)$$

where m and p are integers and p is odd. Note that $L_c(\lambda_1) > L_c(\lambda_2)$ because the coupling coefficient (κ) between two waveguides always increases with increasing wavelength. According to Eq. (5.3), L could be an even multiple of $L_c(\lambda_1)$ at λ_1 and an odd multiple of $L_c(\lambda_2)$ at λ_2 , as illustrated in Fig. 5.2(a) for $m=2$ and $p=1$. We shall call the integer ratio L/L_c the order. Clearly both orders (at the two wavelengths) should be small, since the smaller the orders and the L_c , the shorter the device will be. More importantly, it can be shown, as in Section 5.4.1, that the smaller the order, the more robust the design will be. On the other hand, for both orders to be small, L_c must be very sensitive to wavelength. For instance, if $m = p = 1$, then $L_c(\lambda_1) = 2L_c(\lambda_2)$, i.e., L_c has to change by a factor of 2 in going from λ_1 to λ_2 . Such behavior may be possible only for certain types of waveguide and only for λ_1 and λ_2 that are sufficiently far apart.

Fig. 5.2. Illustration of input with (a) different wavelengths exiting at different ports (wavelength splitting), and (b) different polarizations for a single wavelength exiting at the same port.

The design is further constrained by the need to make the wavelength splitter polarization-independent, such that both the TE and TM polarizations of a given wavelength exit the same port together. This requirement is difficult to meet. In general, it is not possible to satisfy Eq. (5.3) and at the same time have identical coupling length for both TE and TM. However, it is possible to be polarization-independent if the coupling lengths for TE and for TM satisfy the condition: $L = m'L_c^{TE}(\lambda) = (m' + q)L_c^{TM}(\lambda)$ (where q is an even integer), i.e., the orders for TE and TM differ by an even integer, as illustrated in Fig. 5.2(b). This condition assumes that the TE coupling length is larger than that of the TM, which we will see is true for directional couplers based on deep ridge waveguides. Altogether, for the directional coupler to split two wavelengths without splitting the polarizations, it must satisfy the multiple conditions:

$$\begin{aligned} L &= mL_c^{TE}(\lambda_1) = (m + q)L_c^{TM}(\lambda_1) \\ &= (m + p)L_c^{TE}(\lambda_2) = (m + p + q')L_c^{TM}(\lambda_2) \end{aligned} \quad (5.4)$$

where p is odd and q and q' are even. As an example that will be elaborated in the next subsection, we consider the low-order combination $(m, p, q, q') = (1, 3, 2, 4)$,

which implies that $\frac{L_c^{TE}(\lambda_1)}{L_c^{TM}(\lambda_1)} = 3$, $\frac{L_c^{TE}(\lambda_2)}{L_c^{TM}(\lambda_2)} = 2$ and $\frac{L_c^{TE}(\lambda_1)}{L_c^{TE}(\lambda_2)} = 4$. These relatively large

ratios can be achieved only if the coupling lengths are strongly dependent on polarization and wavelength. This strong polarization and wavelength dependence is found only in directional coupler based on strongly guiding ridge waveguides in the single-mode regime. The properties of these ridge waveguides will be discussed in the next section. For other waveguides with small birefringence and wavelength dependence (such as the MMI [117]), the same method may be applied but the design might involve very high orders, which make the device very long. For this reason, we will only consider directional couplers based on single-mode ridge waveguides. For this type of wavelength filter, the general design procedure may be summarized as follows:

- i. For pre-specified values of λ_1 and λ_2 , we calculate the even and odd normal modes (for TE and TM), from which we obtain the coupling lengths, of the directional coupler at the two wavelengths.
- ii. Repeat for various possible waveguide structures to identify the optimum zone.
- iii. From the various coupling length ratios obtained, determine the specific structure that yields a consistent set of (m, p, q, p') that satisfies Eq. (5.4).

5.2 Structural Dependence

We first consider directional couplers made of InP/InGaAsP ridge waveguides of width w and separated by a gap size g . To maximize the wavelength and polarization dependence, w should be in the single-mode regime (which is appropriate, as the directional coupler is a single-mode device), and the gap between the waveguides should be as deep as possible. To minimize the coupling length, the gap should be reasonably small. The effective indices of the supermodes in this directional coupler are calculated using the finite-difference mode solver, taking into account the wavelength dependence of the core refractive index [122]. Fig. 5.3(a) shows the

effective indices of TE and TM polarizations for $w = 0.4 \mu\text{m}$ and $g = 0.1, 0.2$ and $0.3 \mu\text{m}$. From this data, the coupling lengths are calculated using Eq. (5.2), and displayed in Fig. 5.3(b). From the figures, we see that the coupling lengths (i) are fairly small (a few hundred μm), (ii) are always larger for the TE polarization (this is true for deeply etched waveguides); (iii) decrease with increasing wavelength irrespective of the gap size; (iv) are more sensitive to wavelength for the larger gap size; note that from $\lambda_1 = 1.31 \mu\text{m}$ to $\lambda_2 = 1.54 \mu\text{m}$, the TE coupling length changes by a factor of 4 for the case of $g = 0.3 \mu\text{m}$.

Fig. 5.3. InP-based directional couplers: (a) Effective indices for even and odd modes, and (b) coupling lengths, for both TE and TM as a function of gap size g , with $w=0.4 \mu\text{m}$. Inset shows the schematic of the directional coupler.

The ratio of the TE and TM coupling lengths are plotted in Fig. 5.3 as a function of wavelength, and for three values of g . We see that the ratio $L_c^{\text{TE}}/L_c^{\text{TM}}$ can span a wide range of values; in particular, for $w = 0.4 \mu\text{m}$ and $g = 0.3 \mu\text{m}$, we note that $L_c^{\text{TE}}/L_c^{\text{TM}} \sim 3$ at $\lambda = 1.31 \mu\text{m}$ and 2 at $\lambda = 1.54 \mu\text{m}$, which match two of the ratios required. Furthermore, as mentioned earlier, $L_c^{\text{TE}}(1.31 \mu\text{m})/L_c^{\text{TE}}(1.54 \mu\text{m}) \approx 4$ as can be seen from Fig. 5.3(b). This structure, therefore, satisfies approximately all the requirements for a CWDM wavelength filter as specified by Eq. (5.4). By fine-tuning the waveguide parameters around these values, near-perfect match to the requirements can be obtained, as will be shown in the next section.

5.3 Design Examples

As a specific example, Fig. 5.4 shows the simulated power distribution along a 596 μm long directional coupler, with $w=0.395 \mu\text{m}$ and $g=0.30 \mu\text{m}$.

Fig. 5.4. Simulated power in the bar waveguide for TE and TM polarizations of (a) $\lambda=1.31 \mu\text{m}$, (b) $\lambda=1.54 \mu\text{m}$, and (c) the corresponding field profiles along the directional coupler.

With perfect order-matching, it can be seen that the two wavelengths are divided at the cross port and the bar port, respectively, with negligible crosstalk and polarization dependence. The simulation was performed with 3-D FDBPM. The simulations neglect any coupling at the input and output waveguides outside the interaction region, a good approximation since the total coupling here is found to be less than 2% if sharp bends with practical radius of $5 \mu\text{m}$ are used to separate the access waveguides rapidly (this is possible because the waveguides are strongly confined). The coupling lengths obtained by simulation are $L_c^{TE}(1.31 \mu\text{m}) = 596 \mu\text{m}$, $L_c^{TM}(1.31 \mu\text{m}) = 199 \mu\text{m}$, $L_c^{TE}(1.54 \mu\text{m}) = 149 \mu\text{m}$, and $L_c^{TM}(1.54 \mu\text{m}) = 75 \mu\text{m}$. Hence,

at $\lambda_1 = 1.31 \mu\text{m}$, $L = L_c^{TE}(\lambda_1) = 3L_c^{TM}(\lambda_1)$, and at $\lambda_2 = 1.54 \mu\text{m}$, $L = 4L_c^{TE}(\lambda_2) = 8L_c^{TM}(\lambda_2)$.

These orders match the combination (1, 3, 2, 4) that satisfies Eq. (5.4).

We will further show that it is possible to apply the same approach to the Si-SiGe based ridge waveguides. Silicon is attractive for passive photonic device applications due to its low cost and matured fabrication technology. For the SiGe core material, the material refractive index for TM is slightly larger than TE due to the lattice mismatch (strain) between SiGe and Si [123]. This material birefringence will reinforce the waveguide birefringence in the single-mode regime, resulting in a larger overall birefringence compared with the InP based waveguides, and therefore, the coupling length ratios achievable are generally higher than the InP design. In our design example, we assume a waveguide with $\text{Si}_{0.9}\text{Ge}_{0.1}$ as the core material and Si as the cladding. This will give us the indexes summarized in Table 5.1 [123]. The core thickness is assumed to be $0.5 \mu\text{m}$ in order not to exceed the critical thickness for strain relaxation [124]. The DC wavelength filter is characterized by the combination $(m, p, q, q') = (1, 3, 4, 12)$ [i.e., $L = L_c^{TE}(\lambda_1) = 5L_c^{TM}(\lambda_1) = 4L_c^{TE}(\lambda_2) = 16L_c^{TM}(\lambda_2)$], which satisfies Eq. (5.4) for $\lambda_1 = 1.30 \mu\text{m}$, $\lambda_2 = 1.56 \mu\text{m}$. The waveguide parameters are $L = 2829 \mu\text{m}$, $w = 0.495 \mu\text{m}$, and $g = 0.30 \mu\text{m}$. By contrast, the only reported case of a SiGe/Si DC dual-wavelength splitter [125] based on a rib waveguide structure has a length in excess of $5000 \mu\text{m}$, but works only for the TE polarization (based on orders 4 and 5, i.e., $L = 4L_c^{TE}(\lambda_1) = 5L_c^{TE}(\lambda_2)$).

Table 5.1: Refractive index of $\text{Si}_{0.9}\text{Ge}_{0.1}$ and Si materials for TE and TM modes of $\lambda = 1.31 \mu\text{m}$ and $1.55 \mu\text{m}$

Material	$\lambda = 1.31 \mu\text{m}$		$\lambda = 1.55 \mu\text{m}$	
	TE	TM	TE	TM
Si	3.508	3.508	3.476	3.476
$\text{Si}_{0.9}\text{Ge}_{0.1}$	3.5395	3.5478	3.5065	3.5163

Finally, we also note that our method based on matching different orders can be applied to the design of polarization splitter, which is another important component in

integrated optics. This can be seen from the simulation result in Fig. 5.4(b), where at $z=150 \mu\text{m}$ the different polarizations of $\lambda=1.54 \mu\text{m}$ have been separated to distinct ports. Hence, the directional coupler terminated at this point would represent a compact polarization splitter for $\lambda=1.54 \mu\text{m}$. In general, for a polarization splitter operating at a particular wavelength, the directional coupler is designed such that the orders of the coupling length for TE and TM polarizations differ by an odd integer at that wavelength. This design is extremely compact and straightforward compared to other guided-wave polarization splitters reported [124].

5.4 Performance and Sensitivity

5.4.1 Figure of Merit

The most important figure of merit for a wavelength filter is the wavelength isolation or *crosstalk*, which is defined as the ratio between the power of the unwanted wavelength (λ_u) and the total power at the desired wavelength (λ_d) from a specified output port, i.e.,

$$\text{Crosstalk(dB)} = 10 \log_{10} \left[\frac{P(\lambda_u)}{P_{\text{total}}(\lambda_d)} \right], \quad (5.5)$$

In Eq. (5.5), $P(\lambda_u)$ is the power for either TE or TM polarization of the unwanted wavelength that is mixed at the output with the desired wavelength. It is given by either P_b or P_c in Eq. (5.1). Ideally, $P(\lambda_u)$ should be zero, giving zero crosstalk. However, crosstalk will increase when λ , L , or any other waveguide parameters deviate from their optimum values. This is because $P(\lambda_u)$ will increase according to Eq. (5.1), and L_c is a function of wavelength and all the waveguide parameters.

As an example, let us derive quantitatively the effect on the crosstalk at the bar port, where the desired output is $\lambda_2 = 1.54 \mu\text{m}$, due to a small deviation in λ_u from

the nominal value of $\lambda_1 = 1.31 \mu\text{m}$. A small deviation in wavelength, $\Delta\lambda$, will cause a small deviation in coupling length, which may be represented by a dimensionless parameter, δ , such that

$$1 + \delta = \frac{L_c(\lambda_u)}{L_c(\lambda)} = \frac{\Delta n(\lambda)}{\Delta n(\lambda_u)} \cdot \frac{\lambda_u}{\lambda} \approx 1 + \frac{\Delta\lambda}{\Delta n(\lambda_u)} \cdot \frac{\partial \Delta n}{\partial \lambda} \bigg|_{\lambda_u} \quad (5.6)$$

where we have used Eq. (5.2), and set $\lambda_u/\lambda \cong 1$. This gives the relationship between δ and $\Delta\lambda$, which can be written as

$$\delta = \frac{\Delta\lambda}{\Delta n(\lambda_u)} \cdot \frac{\partial \Delta n}{\partial \lambda} \bigg|_{\lambda_u} = 2L_c(\lambda_u) \frac{\partial \Delta n}{\partial \lambda} \bigg|_{\lambda_u} \frac{\Delta\lambda}{\lambda_u} \quad (5.7)$$

Eq. (5.1) can be used to give the power in the bar port at an arbitrary λ that may be different from λ_1 :

$$P_b(\lambda) = \cos^2 \left[M \frac{\pi}{2} (1 + \delta) \right] \approx \sin^2 \left(M \frac{\pi}{2} \delta \right), \quad (5.8)$$

where $M = L/L_c(\lambda_1)$ represents the order of coupling length at λ_1 . Substituting Eq. (5.8) into Eq. (5.5), we obtain the crosstalk as

$$\text{Crosstalk(dB)} = 10 \log_{10} \left[\sin^2 \left(M \frac{\pi}{2} \delta \right) \right] \quad (5.9)$$

where we have assumed $P_{\text{total}}(\lambda_d) = 1$. A typical acceptable crosstalk is -20dB. To meet this requirement, the maximum δ that can be tolerated is

$$\delta = \frac{0.02}{M\pi}. \quad (-20\text{dB crosstalk}) \quad (5.10)$$

Hence, we can see that the smaller the order used, the larger will be the tolerable coupling length deviation δ . Using Eq. (5.7), the wavelength tolerance $\Delta\lambda = |\lambda - \lambda_u|$ is given by

$$\frac{\Delta\lambda}{\lambda_u} = \frac{\delta}{2L_c(\lambda_u) \cdot \left. \frac{\partial \Delta n}{\partial \lambda} \right|_{\lambda_u}} = \frac{0.01}{M\pi L_c(\lambda_u) \cdot \left. \frac{\partial \Delta n}{\partial \lambda} \right|_{\lambda_u}}. \quad (5.11)$$

To maximize $\Delta\lambda$, it is desirable to make M and L_c as small as possible. $\Delta\lambda$ represents the optical bandwidth for a given crosstalk, i.e., the range of wavelengths for which the specified crosstalk is satisfied. It is an important measure of the wavelength sensitivity of the filter. For the CWDM application considered here, the optical bandwidth should be as large as possible so that no temperature stabilization of the laser wavelength is needed.

The same analysis can be applied to the cross port, to either wavelengths, and to either TE or TM. In addition to λ , the coupling length is also dependent on the waveguide structure, namely the gap size and the waveguide width. Similar analysis can be used to derive the degradations in crosstalk due to variations in these dimensions, thereby giving the sensitivity of the device performance to these parameters.

So far, we have not considered the propagation loss in the waveguides. An important parameter is the polarization-dependent loss (PDL), which is not insignificant for single-mode ridge waveguides. The PDL is very sensitive to the waveguide width. For the InP waveguide with $w = 0.4 \mu\text{m}$, previously reported results at $\lambda = 1.54 \mu\text{m}$ are about 9 dB/cm and 7 dB/cm, for TE and TM respectively [127]. The PDL is not excessive if the device is sufficiently short, which is another reason to keep L small. For the design example above where $L \sim 600 \mu\text{m}$, the PDL is about 0.1 dB. However, PDL should be included when considering the crosstalk for different polarizations.

5.4.2 Sensitivity

For the InP example discussed above, the crosstalk at the cross port ($\lambda_d = 1.31 \mu\text{m}$) and the bar port ($\lambda_d = 1.54 \mu\text{m}$) as a function of wavelength deviation for different polarizations are given in Fig. 5.5. The polarization-dependent loss mentioned above has been included in calculating the crosstalk for different polarizations. Note that the crosstalk and the optical bandwidth (for a specified crosstalk) are different for different polarizations and for different wavelengths (ports). In the case of $\lambda_d = 1.3 \mu\text{m}$, the bandwidth is about 20 nm for TE and 10 nm for TM. In the case of $1.54 \mu\text{m}$, the optical bandwidths are 7 and 5 nm for TE and TM, respectively. These results reflect the order dependence of Eq. (5.10): the lower the order, the larger the bandwidth.

Fig. 5.5. The crosstalk as a function of wavelength in μm at (a) the cross port ($\lambda_d = 1.31 \mu\text{m}$), and (b) the bar port ($\lambda_d = 1.54 \mu\text{m}$).

Similarly, Fig. 5.6 shows the effects of dimensional variations in the waveguide width and the gap separation on crosstalk for the InP design example. It can be seen that, to meet a typical crosstalk requirement of -20 dB, the waveguide width must be controlled to within $\pm 5 \text{ nm}$ and the gap size to within $\pm 4 \text{ nm}$. These requirements will in general depend also on the order of the output functions. In the Si/SiGe case, for example, the sensitivity will be worse because of the higher orders involved.

Fig. 5.6. TE and TM crosstalks at the bar port and the cross port of the CWDM directional coupler for various (a) waveguide widths, and (b) gap sizes in μm.

Chapter Summary

We present the first unique design of a polarization-independent dual-wavelength splitter for wavelengths around 1.3 μm and 1.55 μm that is potentially of great interest to PON applications. The filter design is simple compared with the other architectures, and is based on ridge-type lateral directional couplers that can be readily integrated with other planar waveguide devices. Two design examples, based on InP/InGaAsP and Si/SiGe waveguides, are given. This polarization-independent wavelength splitting is achieved by exploiting the polarization dependence of the waveguides to produce coupling lengths that are sensitive to polarization and wavelength. We show that, to split the wavelengths without splitting the polarizations, the coupling lengths must be sufficiently different for TE and TM and for the different wavelengths in order to give the correct required ratios between the TE and TM coupling lengths for the two wavelengths of interest. We also show that the same approach can be applied to the

design of polarization splitter. The crosstalk, optical bandwidth and fabrication sensitivity for the wavelength filter are evaluated.

Author's Related Publications

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1. M. K. Chin, C.-W. Lee, S. Y. Lee, S. Darmawan, "High Index Contrast Waveguides and Devices," *Applied Optics* vol. 44, pp. 3077-3086, 2005.
2. C. W. Lee, S. Darmawan, S. Y. Lee, and M. K. Chin, "Design of Polarization-independent Wavelength Splitter based on Single Conventional Directional Coupler," in *Integrated Photonics Research and Applications* (IPRA), San Diego, U.S.A., pap. IMG2, April 11-13, 2005.

6

Optimization of Room Temperature Inductively Coupled Plasma (ICP) Dry-etching of InP

In the previous chapters, the designs of several building blocks for photonic integration have been presented. Aside from the design work, starting from this chapter, we will look into the fabrication process of photonic devices, which is also an important segment in photonic integration. The fabrication of the photonic devices is in large part similar to the microelectronic devices. Amongst the various processes, dry-etching is one of the critical processes that will determine the final dimension of the devices. Compared with wet-etching, the profiles obtained from dry etching are more precise and anisotropic. The comparison has been drawn previously in Fig. 2.12. Therefore, in this chapter, we will show the study on the different recipes for the dry-etching of InP, including the optimization of room-temperature chlorine-based processes that are different from those usually done at elevated temperature (>200 °C).

6.1 Experiment

6.1.1 Plasma-enhanced Chemical Vapor Deposition (PECVD) Process

The general fabrication process for fabricating a photonic waveguide has been shown previously in Fig. 2.11. In the fabrication, the dielectric thin film deposition is usually the first step. The dielectric film is preferred as the etch mask for the subsequent dry-etching process due to its relatively high thermal stability and strong etch resistance than other types of etch mask, such as metal and photoresist. The dielectric used for our process is SiO₂, and it is deposited by PECVD, which is a process to deposit thin films from a gas state (vapor) to a solid state on some substrate. Chemical reactions occur between these reacting gases after the ignition of plasma from the gas mixture.

The thickness of the dielectric layer deposited is usually in few hundreds of nanometer, and the deposition rate is not only process parameter-dependent, but also chamber dependent. In our fabrication, we have utilized the Unaxis Neutral D200 PECVD machine. Since the SiO₂ layer is used only as an etch mask, its material properties are of no great interest to us. Nevertheless, the deposited thickness under the different duration is plotted in Fig. 6.1. As we can see, the deposited thickness increases quite linearly over time, and the deposition rate is about 140 nm/min. The process parameters are summarized in the inset of the figure. In general, the RF power used is lower than the plasma etching process, and high process pressure is used to increase the deposition rate and dielectric density. The source gases used are silane (SiH₄) and nitrous oxide (N₂O), and the chemical reaction is

Extra safety precautions must be taken as the silane is pyrophoric (ignite spontaneously).

Fig. 6.1. Deposited thickness of SiO₂ by PECVD over time, with inset showing the deposition parameters. The gas flow rates are measured in standard cubic centimeters per minute (sccm).

6.1.2 Reactive Ion Etching (RIE) of SiO₂

After the deposition of SiO₂, the SiO₂ is patterned as an etch mask by photolithography, a process in which the device pattern on a glass photomask is transferred to the photoresist deposited on the SiO₂ layer. For this purpose, Karl Suss mask aligner MJB4 and AZ-5214e positive photoresist are used. The photoresists is sensitive to UV light, and once exposed becomes soluble in solvent. After developing the patterned photoresist is then used as the etch mask for etching the SiO₂. RIE is used for this purpose since the etch depth required is only a few hundreds of nanometers, and the photoresist has reasonable etch resistance to this process. The RIE system used is Oxford Plasmalab 80 Plus.

It is important to compare the etch rate between the target material and the etch mask, because it is always preferred that the etch rate of SiO₂ is higher than that of the AZ-5214e photoresist, so that the etch mask is able to sustain till the complete etching of the target material. After some optimization, the etch results using the optimized recipe is shown in Fig. 6.2. In Fig. 6.2, we show the etch depths of the

photoresist and the SiO₂ over different durations. The primary etchant for the SiO₂ is tetrafluoromethane (CF₄) gas, and small amount of oxygen (O₂) is added to remove the polymer formed on the etched sidewall during the etching process. The chemical reaction that happens primarily between the fluorine and SiO₂ is summarized as followed [127]:

It is found that the etch rate for the SiO₂ is about 40 nm/min, and the etch rate for AZ-5214e is smaller, which is always preferred. However, the selectivity (i.e., ratio of the etch rate for target material against etch mask) is relatively low since the photoresist is a weak material and is not sustainable to plasma attack. Furthermore, the plasma contains slight amount of O₂, which is a good etchant for organic materials. Nevertheless, it is still used here because: (i) the SiO₂ layer that needs to be etched is thin; (ii) it is simpler to be patterned; and (iii) its organic nature as compared to the inorganic dielectric enables easier selection of suitable etchants. For the subsequent etching of the InP, SiO₂ will be used as the etch mask because of the deep etch depth required for ridge waveguide.

Fig. 6.2. Etch depth of SiO₂ and AZ-5214e photoresist against etching time for the optimized recipe using RIE

After the SiO₂ etching is done, the photoresist is removed using acetone, and the samples are then ready for the deep dry etch process using ICP. The ICP machine used is the Oxford Plasmalab System 100. The advantages and operating mechanism of ICP have been discussed in Chapter 2. The schematic of the ICP machine is shown in Fig. 6.3. The loadlock is used for loading the samples without exposure to the residual chlorine. The samples are patterned with uniform strips of SiO₂ of width ranging from 3 to 8 μm . The thickness of the SiO₂ is fixed at about 400 nm. The results in terms of etch rate, sidewall profile and surface roughness will be discussed.

Fig. 6.3. Schematic of the ICP machine used in the optimization of room temperature InP etching.

6.2 Optimization of Room Temperature InP Etching

6.2.1 Methane/hydrogen (CH₄/H₂) Process

CH₄/H₂ recipe has been widely used for the etching of InP. It is demonstrated that the recipe is able to produce better surface and sidewall roughness than the Cl₂-based process [128] due to the high volatility of the etched products, i.e., In(CH₃)₃ and PH₃. The gases used are also non-corrosive and nontoxic, and no substrate heating is required. The recipe is especially popular for the use in RIE machine. The etch rate for the RIE is generally slower due to the lower plasma density. To achieve a higher etch rate, one may increase the plasma energy by raising the RF power. However,

the high-energy plasma will cause severe surface damage. Such damage may affect the performance of the devices; therefore, it is advisable to keep the RF power low at the expense of high etch rate. Due to an additional RF power supply provided (called the ICP power), an ICP is capable of generating high plasma densities independently of the RF power, and this helps in improving the etch rate without causing serious damage to the material surface. With this additional parameter, the process becomes more flexible while recipe optimization becomes more complicated, and hence the Taguchi method [129] is employed.

The five process parameters involved in the optimization are RF power, ICP power, CH₄ gas flow rate, H₂ gas flow rate and process pressure. To reduce the complexity, the ratio of the CH₄ flow rate against the H₂ flow rate is used instead, and the total flow rate of the etchants is fixed at 40 sccm. Without using the Taguchi method, if each parameter is varied between 3 different levels, we would need a total of $3^4=81$ experiments to deduce the effect of each parameter on the etch rate. By using Table L9 in the Taguchi optimization [129], only 9 experiments are needed. The 3 levels assigned to each of the parameters are summarized in Table 6.1. Each process combination in Table 6.1 was carried out for 5 minutes.

Table 6.1: Different levels assigned to the process parameters for the CH₄/H₂ process optimization.

Factor	Level 1	Level 2	Level 3
RF Power (W)	100	200	300
ICP Power (W)	0	500	1000
Pressure (mTorr)	18	25	32
CH ₄ :H ₂ (sccm:sccm)	10:30	20:20	30:10

The linear graphs obtained are shown in Fig. 6.4, summarizing the effect of different process parameters on the mean etch rate. The etch rate is sensitive to, and increases with, both the RF power and the ICP power. The RF power increases the plasma energy, while the ICP power increases the plasma density, and hence, the rate of chemical reaction and physical bombardment of the ions on the surface is

enhanced. However, as is generally the case, a consequence of the higher etch rates is an increased surface roughness. Besides, denser CH_3 ions also tend to promote more polymer formation, and regions covered by the polymer would have no etching at all. Therefore, in the interest of surface smoothness, it is always desirable to keep both RF and ICP powers low as long as the required etch rate is met. Nevertheless, for the CH_4/H_2 process, the etch rate is generally slower. Hence, the main objective in the optimization would be to improve the etch rate, while keeping the surface roughness within reasonable value.

Fig. 6.4. Taguchi linear graphs showing the mean etch rate for different (a) RF power, (b) ICP power, (c) process pressure, and (d) $\text{CH}_4:\text{H}_2$ flow rate, levels.

One can see that the etch rate is relatively insensitive to the pressure level and the flow rate ratio. At higher process pressure, the etch rate is slightly lower because it tends to reduce the efficiency of removing the etching products from the material surface, and the anisotropic etching suffers due to more wayward collisions between the etching species in the plasma. However, the surface is smoother because of less energetic direct bombardment by the plasma. This is illustrated in Fig. 6.5, where the

material surface becomes rougher as the process pressure is reduced, even though the verticality is improved. When the ratio of $\text{CH}_4:\text{H}_2$ is higher than 1, the etch rate is slightly higher due to the more balanced removal rate of the etching products for both indium and phosphorus.

Fig. 6.5. SEM of the waveguide structure when the process pressure is increased from (a) 18mTorr, to (b) 25mTorr, and (c) 32mTorr. The RF power is 100W, ICP power is 400W, and $\text{CH}_4:\text{H}_2:\text{O}_2=30:10:1$ sccm.

With the help from the results in Fig. 6.4 and further fine tuning of the process parameters, the optimum recipe that gives reasonably high etch rate and smooth surface is found to be the combination of 300W for RF power, 100W for ICP power, 20 mTorr for process pressure, and 40:30 sccm for $\text{CH}_4:\text{H}_2$ gas flow ratio. This will yield a DC bias of around 830V. To prevent polymer formation on the SiO_2 surface that may cause overcutting of the sidewall [92,130], and also to maintain a cleaner process chamber for long etching duration, we have added 1 sccm of O_2 gas (2.5% of total flow rate), which has no significant effect on the etch rate. This recipe gives a very smooth surface and a nearly vertical sidewall profile ($\sim 90^\circ$), as shown in Fig. 6.6(a). The rms surface roughness is found to be about 1 nm, as shown in Fig. 6.6(b). The etch rate for InP is about 110 nm/min, which is much higher than the previous reported results using ICP (<40 nm/min) [91] with the similar etchants. Although an etch rate as high as 600 nm/min was reported before with argon addition in ICP [131],

the rms surface roughness (>70 nm) is inferior. Another important process quality is the selectivity with respect to the SiO_2 etch mask. The higher the selectivity, the thinner the SiO_2 that is required, and the easier is the deposition and patterning process. The SiO_2 etch mask selectivity is found to be about 1:26 against InP, which means for every 26 nm of InP etched, 1 nm of SiO_2 will be sputtered away. The relatively low selectivity as compared to the chlorine-based recipe, as we shall see later, is due to the high RF power used, which causes unselective physical bombardment on the material surface. In conclusion, we have developed an optimized process based on $\text{CH}_4\text{:H}_2\text{:O}_2$ that is able to produce reasonable etch rate and selectivity against SiO_2 , smooth material surface and good structural verticality.

Fig. 6.6. (a) SEM of the InP mesa structure under the optimized $\text{CH}_4\text{:H}_2$ recipe, and (b) 3-D Atomic Force Microscopy (AFM) profile of the material surface. The RF power is 300W, ICP power is 100W, process pressure is 20 mTorr and $\text{CH}_4\text{:H}_2\text{:O}_2=40\text{:}30\text{:}1$ sccm.

6.2.2 Chlorine/methane/hydrogen ($\text{Cl}_2\text{/CH}_4\text{/H}_2$) Process

Chlorine is commonly used to etch InP at an elevated temperature to give a high etch rate. The need for elevated process temperature is due to the involatility of the InCl_x product at low temperature. Hence, in our optimization, CH_4 gas is added as the product formed between CH_4 and indium is volatile even at low temperature. Also, H_2 is added to improve the phosphorus removal and to improve the etching surface.

However, as complementary gases to Cl_2 , their flow rates will be smaller as compared to the chlorine flow rate (also, higher H_2 flow rate will cause formation of HCl). As we shall see later that: (i) the InP etch rate improves for the $\text{Cl}_2/\text{CH}_4/\text{H}_2$ gas combination process, as compared to the pure CH_4/H_2 process; and (ii) with pure chlorine and high RF and ICP powers, very high etch rates can be obtained but the surface is rough due to the formation of InCl_x clusters and the damages caused by the strong physical bombardment. Therefore, CH_4 and H_2 are needed to improve the indium removal while maintaining reasonably high etch rate, without the need of raising the RF and ICP powers. Generally as observed by SEM, the etched material surface is much cleaner than pure CH_4/H_2 process due to less polymer formation caused by chlorine cleaning.

The six process parameters involved in the optimization are the RF power, ICP power, Cl_2 gas flow rate, CH_4 gas flow rate, H_2 gas flow rate and process pressure. To reduce the complexity, the pressure is assigned to two levels, one representing the high pressure region and another representing low pressure region. Without using the Taguchi method, if each of the 5 other parameters is varied between 3 different levels, we will need a total of $2 \times 3^5 = 486$ experiments to deduce the effect of each parameter on the etch rate. By using Table L18 in the Taguchi optimization [129], only 18 experiments are needed. The various levels assigned to the parameters are summarized in Table 6.2. Each etching process is carried out for 3 minutes.

Table 6.2: Different levels assigned to the process parameters for the $\text{Cl}_2/\text{CH}_4/\text{H}_2$ process optimization.

Factor	Level 1	Level 2	Level 3
RF Power (W)	100	200	300
ICP Power (W)	0	500	1000
Pressure (mTorr)	4	15	
Cl_2 (sccm)	5	10	15
CH_4 (sccm)	0	4	8
H_2 (sccm)	0	4	8

Fig. 6.7 shows the linear graphs summarizing the effect of different process parameters on the mean etch rate. Similar to the previous process, the etch rate improves with increasing RF and ICP powers. It also improves with higher concentration of chlorine gas and lower CH_4 and H_2 flow rates. As CH_4 and H_2 flow rates increase, the chlorine gas is more diluted and the etch rate is reduced. With pure Cl_2 and high ICP power, very high etch rates can be obtained but the surface is rough due to the formation of InCl_x clusters and plasma damage. Hence, CH_4 and H_2 are needed to reduce the cluster formation, even though the etch rate will be reduced.

Fig. 6.7. Taguchi linear graphs showing the mean etch rate as a function of (a) RF power, (b) ICP power, (c) Cl_2 flow rate, (d) CH_4 flow rate, (e) H_2 flow rate, and (f) process pressure.

Based on the above results, as a compromise between high etch rate and smooth surface, we selected the RF power, Cl_2 , CH_4 and H_2 flow rates to be 100W, 10 sccm, 8 sccm and 4 sccm, respectively. For the Cl_2 gas, 10 sccm is chosen as a compromise between etch rate and surface quality, as reactive gases like chlorine tend to cause more damage to the surface [128]. 8 sccm of CH_4 flow rate is chosen to avoid the formation of indium-rich surface. A moderate H_2 flow rate is chosen to smoothen the etching surface without reducing the etch rate seriously. The process pressure is set at 4 mTorr to improve the verticality of the sidewall profile and also the InCl_x removal.

With these parameters set, the ICP power is varied to investigate its effect on the etch rate, surface quality and structural verticality. As seen in Fig. 6.8, the etch rate increases almost linearly with the ICP power. The verticality of the etch profile improves with increasing ICP power, as evident from the SEM profiles shown in the insets, probably due to the increase in anisotropic physical bombardment at higher plasma density. Therefore, it is preferably to have higher ICP power, but yet not too high as to cause undercut when the chemical reaction dominates.

Fig. 6.8. InP etch rates for different ICP powers, with RF power set at 100W, process pressure set at 4 mTorr, Cl_2 , CH_4 and H_2 flow rates set as 10, 8 and 4 sccm, respectively.

These results suggest that a wide range of etch rate and profiles can be obtained by selecting the appropriate ICP power. At zero ICP power, the etch rate is insignificant. The relatively high etch rate and anisotropic etching obtained at reasonably high ICP power, even without intentional substrate heating, suggests that the InCl_x etch products are being efficiently removed by ion-assisted desorption, which prevents the formation of InCl_x layer [103]. The heat generated by the high ICP power ($\sim 100^\circ\text{C}$) could have also improved the volatility of the InCl_x product.

Fig. 6.9(a) shows the SEM picture of the mesa structure etched with an ICP power of 1200W. The DC bias in this case is about 310V. Aside from the slight overcut, the sidewall is very vertical ($\sim 90^\circ$). The etch rate achieved is around 800 nm/min, which is a significant increase from the CH_4/H_2 process. The selectivity between SiO_2 and InP is about 1:35, which is also better than the CH_4/H_2 process, possibly due to the higher ICP power and lower RF power used that increase the highly selective chemical reaction. The 3-D AFM plot is shown in Fig. 6.9(b), which shows an rms surface roughness of about 4 nm. This is rougher than the CH_4/H_2 process, but nevertheless, it is still within acceptable value. This is predictable as higher etch rate tends to increase the surface roughness.

Fig. 6.9. (a) SEM of the InP mesa structure under the optimized $\text{Cl}_2:\text{CH}_4:\text{H}_2$ recipe, and (b) 3-D AFM profile of the material surface. The RF power is 100W, ICP power is 1200W, process pressure is 4 mTorr and $\text{Cl}_2:\text{CH}_4:\text{H}_2=10:8:4$ sccm.

The etch depth as a function of etch time is shown in Fig. 6.10, which shows that the etch depth increases quite linearly with time, and there is no observable etching for the first 30 seconds. This may be because the plasma is still stabilizing within that short period. The etch depth of the SiO₂ etch mask is not shown here because the etch depth is insignificant as compared to the InP etch depth at this short period of etch time.

Fig. 6.10. InP etch depth at different etch time, with RF power set at 100W, ICP power set at 1200W, process pressure set at 4 mTorr, Cl₂, CH₄ and H₂ flow rates set as 10, 8 and 4 sccm, respectively.

6.2.3 Chlorine/Nitrogen (Cl₂/N₂) Process

In the Cl₂/CH₄/H₂ process, due to the use of CH₄, polymer could form on the samples and chamber (requires frequent wet-cleaning). Furthermore, the use of H₂ could cause passivation on the material, which is undesirable for active devices [90]. As an alternative, Cl₂/N₂ recipe has been used for the etching of InP at elevated temperatures [85, 95]. Due to the lack of methane gas, polymer formation is avoided and the etch rate could be much improved. Without the hydrogen gas, the material passivation is also avoided. At low temperature, the etching mechanism of InP using Cl₂/N₂ can best be described as accelerated ion assisted chemical etching process, in which the nitrogen ions are accelerated by the DC bias and promote the chlorine chemical etching of indium by physical sputtering. The addition of N₂ is able to

produce N_2^+ ions which can sputter off the indium atoms and the $InCl_x$ clusters [101]. The use of lighter nitrogen ($Z=14$) ions produces less surface damage as compared with the use of argon ($Z=40$).

By utilizing the same optimization technique, we have demonstrated that the Cl_2/N_2 recipe is able to achieve a higher etch rate at lower ICP power, as compared to the $Cl_2/CH_4/H_2$ recipe. In our optimized recipe, the $Cl_2:N_2$ ratio is found to be 10:5 sccm, the ICP power is 700W, and the RF power is 125W, while the process pressure is 4 mTorr. These yield a DC bias of about 410V. The SEM photographs of the etch profile are shown in Fig. 6.11(a). The etch rate is found to be about 2 $\mu m/min$, which is much higher than any other optimized recipes that we have. The selectivity against oxide is found to be 55:1, which is one of the highest reported so far. The RMS roughness of the surface is found to be 6.85 nm, as presented in Fig. 6.11(b). The etch rate-surface roughness results up to this point show that: the higher the etch rate, the rougher the surface. This is probably because faster etching tends to create more surface damage that causes irregularity on the surface. It is also likely to be caused by the physical bombardment of the N_2^+ ions.

Fig. 6.11. SEM photos of the mesa structure etched using the Cl_2/N_2 optimized recipe, with (a) showing the cross section profile, and (b) the corresponding 3-D AFM surface profile. The RF power is 125W, ICP power is 700W, process pressure is 4 mTorr, Cl_2 flow rate is 10 sccm and N_2 flow rate is 5 sccm.

It is found that the flow rate ratio of $\text{Cl}_2:\text{N}_2$ plays an important role in deciding the sidewall profile. The higher the ratio, the greater is the sidewall undercut, indicating the dominance of chemical etching. The surface also gets rougher, possibly due to the formation of more InCl_x clusters at high Cl_2 concentration. It is also found that the etch rate reduces with decreasing chlorine concentration. Other studies [91] have shown that physical bombardment mechanism (by the nitrogen ions) generally produces much lower etch rate than chemical etching (by the chlorine species). Hence, an optimum $\text{Cl}_2:\text{N}_2$ flow ratio is required to give a reasonably high etch rate while preserving acceptable surface quality, which is found to be 10:5 sccm in our case.

6.3 Device Measurement

6.3.1 Uniform High-Index-Contrast Waveguides

In this subsection, one of the ICP etching recipes will be tested in fabricating the InP HIC waveguide. The flow of the process was summarized in Fig. 2.11 in Chapter 2; hence, it will not be presented here. The layer structure of the waveguide is shown in Table 6.3, and the corresponding room temperature photoluminescence (PL) result is shown in Fig. 6.12. The PL laser source used has a wavelength of 1064 nm; hence, the InP substrate will not be excited. We can see that the actual PL peak wavelength corresponds to the waveguide core (i.e., layer 3), which is around 1310 nm, deviates slightly from the design value. But nevertheless, it is still acceptable for waveguide application, since the core index is still higher than that of the claddings to provide sufficient light confinement.

Table 6.3: Layer structure of the waveguide

Layer Number	Material	Thickness (nm)	Doping Type	Doping
6	InGaAs	100	P+	$>1 \times 10^{19}$
5	InP	1400	P	3×10^{16}
4	InP	100	-	-
3	InGaAsP ($\lambda=1.35 \mu\text{m}$)	400	-	-
2	InP	100	-	-
1	InP	2900	N	3×10^{16}
	InP substrate	350000	N	$\sim 1 \times 10^{18}$

Fig. 6.12. Photoluminescence result of the wafer with waveguide structure. The measurement is done under room temperature ambient.

Based on the layer structure, the waveguide loss is expected to be high due to the free-carrier loss since the cladding layers are heavily doped. Furthermore, ridge structure in nature tends to give higher loss because of the lateral high index contrast interface. The waveguides that we fabricated are $3 \mu\text{m}$, $4 \mu\text{m}$, $5 \mu\text{m}$ and $8 \mu\text{m}$ in width. In the measurement setup, the input laser used is a tunable laser, with wavelength tuning range of 1510-1630 nm. The laser is coupled directly into the waveguide by using a SMF and the output mode of these waveguides are collected by a collimating lens and projected onto an infrared camera, then being analyzed by the supplier-provided software. Fig. 6.13(a) shows the mode profiles obtained from the output of some of the waveguides, and Fig. 6.13(b) presents an example of the Fabry-Perot (FP) measurement result of the waveguides. FP method [132] is used in our measurement, instead of the conventional cut-back method because it is non-destructive and it decouples the fiber coupling loss from the measurement results. The result obtained will contain FP fringes, as similar to those in the FP laser.

Fig. 6.13. (a) Output modes of a 5 μm and an 8 μm waveguides, and (b) FP fringes obtained from the 8 μm waveguide measurement, with insets showing the mode profiles at the maxima and minima wavelength.

From these FP fringes, the losses can be calculated from the ratio between the maximum and minimum intensities. The oscillation in output power is due to interference between the light reflected at both the waveguide facets. The propagation loss can be obtained by [132]

$$\alpha L = \ln \left(\frac{RK}{1 - \sqrt{1 - K^2}} \right) \quad (6.1)$$

where α is the absorption coefficient, L is the waveguide length, R is the reflectivity, which is the same at both facets and is approximately 0.3 for InP waveguide, and K is the intensity (I) contrast given by

$$K = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \quad (6.2)$$

In decibel (dB), the waveguide loss per centimeter length is given by

$$\alpha(\text{dB/cm}) = \frac{4.34 \ln \left(\frac{RK}{1 - \sqrt{1 - K^2}} \right)}{L}. \quad (6.3)$$

One of our obtained results show measured losses of about 4.5 dB/cm and 3.5 dB/cm for the 5 μm and 8 μm waveguides, respectively. Other narrower waveguides give higher losses, in which the 3 μm waveguide loss is about 11 dB/cm, and the 4 μm waveguide loss is about 5.4 dB/cm. It is found that the narrower the waveguide, the higher the waveguide loss. This is expected as the sidewall effect due to the high index contrast and the sidewall roughness will become more significant for narrower waveguide. Furthermore, the substrate leakage loss will be higher for narrower waveguide. Although these results are not the best reported, they show that our optimized room temperature recipe is able to produce waveguides with reasonable results. The optimized recipe used in this study is the $\text{Cl}_2/\text{CH}_4/\text{H}_2$ recipe.

6.3.2 Multimode Interferometer (MMI)

We have also fabricated some MMIs. The MMIs fabricated are the 1×2 MMI splitter. The SEM images of the 1×2 MMI are shown in Fig. 6.14. The MMI body width and length are 12 μm and 145 μm , respectively, and the ports are all 4 μm wide. The fabrication process of a MMI is identical to that of the uniform waveguide. The reason for having rounded joints between the MMI body and waveguide ports is to avoid the UV-diffraction (the rounding is designed into the photomask) at the sharp corner

during the photolithography. Besides, it will also give a smoother transition for the waveguide mode.

Fig. 6.14. SEM of the fabricated 1×2 MMI, showing (a) the input region, (b) the output region, and (c) the output mode as observed by the infrared camera.

The measured result shows a good splitting of the MMI. In one of the results, the output power at the two output ports are about 0.79 μW and 0.82 μW, respectively for an input power of about 140 μW from the optical fiber. This yields a splitting ratio of almost 50:50, and an insertion loss of about 19 dB. The high loss is mainly due to coupling loss. Additional losses arise from: (i) the high waveguide propagation loss and the length of the MMI; (ii) the bending loss at the output ports; and (iii) the whole

MMI is quite long, which is about 2 mm. This gives an approximated total propagation loss of about 9.5 dB/mm. Fig. 6.14(c) shows the output mode as observed from the mode analyzer, where we can see the mode intensities are quite similar. The input laser wavelength is 1.55 μm .

Chapter Summary

In this chapter, the various recipes for the etching of InP are studied. A near-optimum recipe for the room temperature $\text{Cl}_2/\text{CH}_4/\text{H}_2$ process is achieved. Another optimum recipe without CH_4 , which is based on Cl_2 and N_2 is also obtained. The results for these recipes are summarized in Table 6.4. Generally at room temperature, with the addition of chlorine, the etch rate is much increased. However, due to the high etch rate and involatility of the products, the surface tends to be rougher. Hence, other gases has to be added to improve the surface quality, even though the etch rate might be reduced. The ICP power used is also much higher than those done under elevated temperature. It is very likely that the ion-assisted InCl_3 removal and the thermal effect created by the high ICP power are the major factors behind the high etch rates obtained in the unheated ICP process developed here. The waveguides and MMIs fabricated by one the recipes are also measured, and the results have been discussed. The results are not the best reported, but nevertheless, they show that our etching recipe works.

Table 6.4: Summary of the optimized room temperature InP etching recipes

	CH_4/H_2	$\text{Cl}_2/\text{CH}_4/\text{H}_2$	Cl_2/N_2
Gases used	$\text{CH}_4 = 40 \text{ sccm}$ $\text{H}_2 = 30 \text{ sccm}$ $\text{O}_2 = 1 \text{ sccm}$	$\text{Cl}_2 = 10 \text{ sccm}$ $\text{CH}_4 = 8 \text{ sccm}$ $\text{H}_2 = 4 \text{ sccm}$	$\text{Cl}_2 = 10 \text{ sccm}$ $\text{N}_2 = 5 \text{ sccm}$
RF power (W)	300	100	125
ICP power (W)	100	1200	700
Pressure (mTorr)	20	4	4
Etch rate (nm/min)	110	800	2000
RMS roughness (nm)	1	4	6.85
Selectivity	1:26	1:35	1:55

Author's Related Publications

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1. C.-W. Lee, D. Nie, T. Mei, M.-K. Chin, "Study and optimization of room temperature inductively coupled plasma etching of InP using $\text{Cl}_2/\text{CH}_4/\text{H}_2$ and CH_4/H_2 ," *Journal of Crystal Growth*, vol. 288, pp. 213-216, 2006.
2. C.-W. Lee, M.-K. Chin, "Room-temperature inductively coupled plasma etching of InP using Cl_2/N_2 and $\text{Cl}_2/\text{CH}_4/\text{H}_2$," *Chinese Physics Letter*, vol. 23, pp. 903-906, 2006.
3. C.-W. Lee, D. Nie, T. Mei, R. Akkipeddi, M. K. Chin, "Taguchi optimization of Inductively Coupled Plasma etching of InP using CH_4/H_2 and $\text{Cl}_2/\text{CH}_4/\text{H}_2$ under room temperature," *International Conf. on Materials for Advanced Applications (ICMAT)*, Singapore, pap. MA-6-OR31, July 4-8, 2005.

7

Quantum Well Intermixing (QWI) for Integration of Passive and Active Devices

In Chapter 6, we have discussed the various dry-etching recipes that are important for the fabrication of photonic devices. Another important process relevant to photonic integration is quantum-well intermixing (QWI), which is a post-growth process for generating different material bandgaps on a single semiconductor substrate. The technique is particularly useful for passive-active device integration, which we shall present in the next chapter. The technique not only avoided the scattering and reflection losses at the passive-active interface, as compared to other techniques based on selective area growth, the process step is also simpler. In this chapter, we will discuss two techniques for QWI. They are the impurity-free vacancy-enhanced disordering (IFVD) and plasma-enhanced QWI (PE-QWI) with the aid of our ICP system. These two techniques are carried out with the facilities we have.

For passive-active device integration, the passive region is required to have a bandgap wavelength much smaller than the operating wavelength in order to minimize absorption loss. Since QWI usually gives a blueshift, the starting material must have a bandgap energy corresponding to the operating wavelength for the

active device, while QWI is carried out in the passive region to give it a blueshift in order to make it transparent at the operating wavelength, which is 1.55 μm in our case.

7.1 Intermixing Mechanism

For QWI of multiple quantum wells (MQW) structure, the mechanism has been widely reported in the literature. Here, we shall describe very briefly on how the techniques of our interest work. Generally, it involves the creation of defects on the sample by various means, followed by high temperature annealing that promotes the propagation of the defects into the quantum well region. Inter-diffusion of the elements will happen, and this modifies the bandgap of the quantum wells and barriers. Usually the more defects generated, the higher the inter-diffusion, and the larger the bandgap modification.

For the PE-QWI using the ICP-generated plasma, the near-surface defects are created by the argon plasma bombardment on the exposed area. The near-surface defects created during plasma exposure propagate into the MQW region during the annealing step. The arrival of defects in the MQW region enhances the inter-diffusion of the group III and group V elements, resulting in a wider bandgap in the quantum well and hence a blueshift in the corresponding wavelength. As reported before [9]: (i) the higher the plasma density, the more the defects generated; (ii) the longer the plasma exposure time, the more defects are generated, but the damage depths remain constant. However, the defect density will saturate after certain exposure time.

For the IFVD technique, it involves the deposition of a dielectric cap layer, such as SiO_2 or Si_3N_4 onto the MQW substrate, followed by a rapid-thermal anneal (RTA) which promotes the inter-diffusion between the vacancies and atoms. Vacancies could be generated on the substrate during the dielectric deposition stage. Depending

on the dielectric material, it could encourage or inhibit the intermixing. The difference in the thermal expansion coefficients of the dielectric and the topmost layer of the substrate is the important factor that determines the extent of bandgap manipulation. If the substrate surface is under compressive stress during annealing, i.e., the thermal expansion coefficient of the dielectric cap is smaller than that of the top layer of the substrate, the vacancies will diffuse across the quantum well region and promote intermixing. If it is under tensile stress, the vacancies will be trapped and hence, the intermixing is limited [106]. For examples, due to the extent of difference in thermal expansion coefficients: (i) the SiO_2 -InGaAs or Si_3N_4 -InP combination tends to induce larger blueshift than the SiO_2 -InP or Si_3N_4 -InGaAs combination [133], and (ii) the TiO_2 has been used to suppress the intermixing in InGaAs/GaAs quantum dots [106].

In Table 2.1 previously, we have summarized the thermal expansion coefficients for the various materials. In our application, as we shall see later, the material of the topmost layer is $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, which is the p-type electrical contact layer. For this material, SiO_2 is found to be a suitable dielectric to induce intermixing. Due to the difference in thermal expansion coefficient at the annealing temperature, a strain effect exists at the interface between the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer and the SiO_2 film during the annealing stage. By referring to Table 2.1, the thermal expansion coefficient of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ is about ten times that of SiO_2 . As a consequence, the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ surface layer is under compressive strain. Under this condition, the out-diffusion of group III atoms into the SiO_2 film, leaving behind vacancies, is an energetically favored process because it minimizes the strain in the system. The gallium component in the top layer will dissolve into the SiO_2 layer, forming Ga_2O_3 [11] and creating more vacancies. All these vacancies will diffuse into the quantum well region and promote inter-diffusion across the wells and barriers, thus modifying the material bandgaps.

7.2 Experiment

The wafers used are obtained from IMRE and grown using MOCVD. Table 7.1 shows the layer structure of all the wafers. Two wafers are provided: one with three quantum wells, and another with six quantum wells. In the experiment, the wafers are diced into smaller pieces. The samples are divided into three categories: (i) samples deposited with SiO₂ cap layer in order to observe the effect of IFVD; (ii) samples exposed to argon plasma with certain parameters in order to observe the effect of PE-QWI; and (iii) as grown samples in order to observe the thermal shift (i.e., shift due to thermal annealing) alone. The SiO₂ layer is 200nm thick. Subsequently, all the samples are annealed using the Jipelec Jetstar 100 rapid thermal processing (RTP) system in flowing N₂ ambient. During the annealing, the samples are covered with InP substrate on both sides to create group III over-pressure on the samples to prevent out-diffusion of group-III element.

Table 7.1: Layer structure of the epitaxy wafers used in the QWI experiments. The difference between the two wafers lies in the number of quantum wells, q . QW—quantum well, QWB—quantum well barrier

Layer Number	Material	Thickness (nm)	Doping Type	Doping
12	InGaAs	200	P+	1×10^{19}
11	InP	1300	P	1×10^{18}
10	InP	150	P	5×10^{17}
9	InGaAsP ($\lambda=1.30 \mu\text{m}$)	5	P	5×10^{17}
8	InP	50	P	5×10^{17}
7	InGaAsP ($\lambda=1.15 \mu\text{m}$)	80	P	2×10^{17}
6	InGaAsP ($\lambda=1.24 \mu\text{m}$)	70		
5 (QW)	InGaAsP ($\lambda=1.58 \mu\text{m}$)	$5 \times q$		
4 (QWB)	InGaAsP ($\lambda=1.24 \mu\text{m}$)	$10 \times (q-1)$		
3	InGaAsP ($\lambda=1.24 \mu\text{m}$)	70		
2	InGaAsP ($\lambda=1.15 \mu\text{m}$)	80	N	4×10^{17}
1	InP buffer	750	N	1×10^{18}
	InP substrate	350000	N	$\sim 1 \times 10^{18}$

7.3 Results and Discussions

In PE-QWI, the ICP system is preferred over the RIE system as it is able to produce higher plasma density, which leads to higher defect density. The subsequent annealing treatment is required to drive the surface defects to the underlying QW region, and also to remove the induced lattice damage on the sample surface [9]. However, annealing alone also causes a blueshift, known as thermal blueshift, because of the built-in defects in the as-grown samples. Large thermal blueshift is an indication that the sample has a lot of built-in defects. Ideally, the thermal shift should be small, so that the blueshift is controlled solely by the external process (either plasma or IFVD). The difference between the QWI-induced blueshift and the thermal blueshift is referred to as the differential shift, and it is always desirable to have larger differential shift in the intermixed region.

Fig. 7.1 shows the effect of the argon plasma PE-QWI on the samples, along with the anneal-only samples. The samples are exposed to argon plasma generated by ICP, with RF power set at 450W, ICP power set at 500W, argon flow rate set at 100 sccm and process pressure set at 60 mTorr. The recipe is modified from the one developed by the previous researcher [9]. The DC bias is about 850V. All the samples are exposed to the plasma for around 2.5 minutes. Then, each of the samples, along with an as-grown sample, is annealed by RTA at different temperatures. The annealing time is set at 120s. It is found that for both the 3-QW and 6-QW structures, they are able to produce a maximum differential blueshift of around 80 nm for 120s of annealing at 750°C. The differences in the magnitude of blueshift for the two samples are relatively insignificant, and hence, the level of inter-diffusion is insensitive to the number of quantum wells. As temperature increases, the blueshift increases for the PE-QWI samples and the anneal-only samples, which are due to the higher defects inter-diffusion promoted by the high temperature. At temperatures lower than 650°C, the thermal shift and the plasma-induced shift are not significant. At temperatures

higher than 750 °C, the thermal shift is too large that it may not be suitable for active device application; furthermore, at such temperature the QW structure may change into a homogeneous alloy [11].

Fig. 7.1. Blueshift induced by the two QWI techniques, i.e., the PE-QWI and the IFVD techniques on the (a) 3 quantum wells, and (b) 6 quantum wells structures. The as-grown samples are annealed alongside.

In the argon PE-QWI, bandgap blueshift is always observed, and this implies that the diffusion length ratio, k (i.e., diffusion lengths of group V element over group III element) for the material is likely to be higher than unity [134-135]. The explanation is as follows: During the early stage of plasma exposure, both group III and group V defects are generated at the near-surface due to the physical bombardment. However, because of the relatively high sputtering rate, which is estimated to be around 200 nm/min, the InGaAs cap layer is easily sputtered away leaving the InP

underneath exposed. Then, the P atoms are preferentially sputtered and create an abundance of group V vacancies [136]. As a result, the inter-diffusion of group V element will dominate, which means $k > 1$, and therefore blueshift is always observed. Also, due to the higher activation energy for group V inter-diffusion [135], the blueshift will only prevail at higher annealing temperature and increases with temperature.

In Fig. 7.2, we show the dependence of bandgap blueshift on the plasma exposure time, which is an important factor in deciding the extent of blueshift. The figure shows the representative case of annealing at 650 °C for 120s. The optimum exposure time for generating highest blueshift is found to be 3 minutes. For longer exposure time, the blueshift saturates and start to decrease slightly. This can be understood that most of the defects will be created in the early stage of plasma exposure and, as the defects start to build up, fewer defects will subsequently be created. Furthermore, the argon plasma might sputter away some defects that were previously generated, and hence, the blueshift decreases.

Fig. 7.2. Bandgap blueshift for the different argon plasma exposure times. The samples are annealed subsequently at the 650 °C for 120s.

It is also not recommended to have a long exposure time as the sputtering rate due to the argon plasma on the material is quite severe, which is about 200 nm/min. This will damage the surface and the samples may not be suitable for the subsequent device fabrication. Hence, we will look into the IFVD method, which is simpler and does not cause any surface damage.

It is found that the IFVD is able to produce even higher differential shift at the same annealing temperature and annealing time. Fig. 7.1 also shows the result after annealing for the SiO₂ capped samples. It shows, as similar to the PE-QWI technique, the blueshift increases with the annealing temperature. Nevertheless, in this case, the blueshift for the 3 QWs and 6 QWs samples are nearly identical, which again proves that the blueshift magnitude is insensitive to the number of quantum wells. The differential blueshift for IFVD is up to 120 nm, which is higher than the PE-QWI technique. This blueshift magnitude is preferred because the operating wavelength will be much larger than the passive-bandgap wavelength.

The magnitude of blueshift is also dependent on the annealing time, as shown in Fig. 7.3. The longer the annealing time, the higher the blueshift. This is probably because longer annealing time induces more inter-diffusion in the material. Nevertheless, 120s has proved to be sufficient in generating the required blueshift. Longer annealing time may not be appropriate as it might cause the total disorder of the MQW structure, which can be observed from the severe reduction of the PL peak. Generally for both QWI techniques, no significant broadening of linewidth is observed from the PL spectrum.

Fig. 7.3. Blueshift generated by the IFVD with SiO₂ cap layer and the RTA only samples for different annealing time. The annealing temperature is set at 750°C.

From the discussion above, it is found that the IFVD is a more suitable way for our active-passive devices integration. For the wafer used, the etch stop layer (i.e., layer 9 in Table 7.1) is meant to enable a better control on the highly selective wet-etching in the fabrication of rib waveguide. The chemical etchant for the etching of InP (e.g., mixture of hydrochloric acid (HCl) and de-ionized water) will stop right at this layer and the underneath InP layer will be protected. For our application on ridge waveguide, however, this layer is not needed. This layer was meant for other research work carried out in IMRE. Hence, we will be using another wafer without the etch stop layer, also provided by IMRE, for our actual device fabrication, with slight modification. The layer structure is shown in Table 7.2.

Table 7.2: Layer structure of the epitaxy wafers used in the actual integrated device fabrication.

Layer Number	Material	Thickness (nm)	Doping Type	Doping
10	InGaAs	50	P+	1×10^{19}
9	InP	1000	P	2×10^{18}
8	InP	400	P	5×10^{17}
7	InGaAsP ($\lambda=1.15 \mu\text{m}$)	120		
6	InGaAsP ($\lambda=1.24 \mu\text{m}$)	100		
5 (QW)	InGaAsP ($\lambda=1.58 \mu\text{m}$)	5×3		
4 (QWB)	InGaAsP ($\lambda=1.24 \mu\text{m}$)	10×2		
3	InGaAsP ($\lambda=1.24 \mu\text{m}$)	100		
2	InGaAsP ($\lambda=1.15 \mu\text{m}$)	140		
1	InP buffer	700	N	3×10^{18}
	InP substrate	350000	N	$\sim 1 \times 10^{18}$

Fig. 7.4 presents the results for the IFVD on the actual samples. The SiO₂ cap layer is also 200 nm thick. Similar bandgap blueshift is observed, but the magnitude of differential blueshift is much higher for this wafer at 700 °C, which is about 100 nm. The increase in blueshift may be because of the absence of etch stop layer, which in some degree obstructs the propagation of defects throughout the homogeneous InP cladding layer and increase the critical temperature in which a large blueshift is triggered. For higher temperature, it is found that the differential blueshift is not improved due to the relatively higher thermal shift.

Fig. 7.4. Blueshift of the actual samples for the different annealing temperature, with the annealing time set at 120s.

It is found that 120s is a reasonable annealing time to generate sufficient differential blueshift for our application, which is estimated to be around 100 nm. The blueshift for annealing at 700°C against different annealing time is shown in Fig. 7.5. It shows that for shorter annealing time, the differential blueshift is much smaller, but at 120s, it is the largest. For longer annealing time, the differential blueshift reduces. This is probably because of the saturation of vacancies effect in addition to the increase of thermal shift.

Fig. 7.5. Blueshift of the actual samples for the different anneal time, with the anneal temperature set at 700°C.

From all of our IFVD results, blueshift is always observed. From the literature, bandgap blueshift with SiO₂-capped IFVD is also reported by other researchers [7,11,106,133,137-138]. This probably because: under the SiO₂ layer, the gallium atom of the top layer will out-diffuse into the cap layer and cation vacancies are generated, while the SiO₂ cap layer itself also contains certain amount of anion vacancies due to its porosity [138]. These vacancies will promote the intermixing of the different elements in the quantum well with the surrounding region, and the net effect is an inter-diffusion that leads to bandgap blueshift.

7.4 Measurement of Intermixed Waveguides

Before we proceed on to the fabrication of the actual integrated device, we have fabricated some uniform HIC waveguides, in which we have applied the IFVD QWI to create both active and passive region on a single waveguide. The waveguides will then be cleaved to separate the different regions and be measured separately. This is to verify whether the QWI will affect the waveguiding capability of the sample. We have utilized the IFVD with RTA at 700°C for 120s, and the waveguide fabrication process is shown in Fig. 2.10. The structure of the epitaxy substrate used is shown in Table 7.1, with three quantum wells. The PL spectrum of the sample is shown in Fig. 7.6, where we can see that the blueshifts are about 140 nm and 40 nm for the passive region and the active region, respectively. This gives rise to a differential blueshift of 100 nm.

Fig. 7.6. PL spectrum of the 3 quantum wells waveguide sample after the IFVD QWI with RTA at 700°C for 120s. The PL is done at 77K ambient.

The output mode profiles of the waveguides are shown in Fig. 7.7, where we can see that the mode profiles of the intermixed (passive) waveguides are brighter than those for the non-intermixed (active) waveguides. The loss measurement shows that the propagation losses for the intermixed and the non-intermixed waveguides are 23 dB/cm and 69 dB/cm, respectively for the 5 μm wide waveguides, and 44 dB/cm and

77 dB/cm, respectively for the 4 μm wide waveguide. These show a significant improvement of the waveguide losses after the QWI, because the material bandgap of the intermixed region has been blueshifted further from the input laser wavelength, which is around 1.55 μm region. The generally high waveguide loss could be due to: (i) the carrier absorption loss caused by the heavily doped region, (ii) the substrate leakage loss due to the thin waveguide core, which comprises only the MQW region and the graded index region, and (iii) the sidewall roughness caused by the ICP dry-etching. Nonetheless, the results show that the waveguiding property is still conserved after the QWI, and hence, we will proceed on to discuss on the integrated device fabrication in the next chapter.

Fig. 7.7. Output mode profiles of the waveguides, with (a), (b) from the intermixed region, and (c), (d) from the non-intermixed region.

Chapter Summary

In this chapter, we have presented the study on two QWI techniques on our MQW wafers. In the PE-QWI method, the sample is exposed to argon plasma generated by the ICP, while for the IFVD method, the sample is deposited with 200 nm thick SiO_2 cap layer. Both processes are followed by annealing with a RTP

machine. The two techniques are both able to generate significant differential blueshift, but the IFVD gives higher differential blueshifts at a lower annealing temperature. The maximum magnitude of blueshift achieved by IFVD is about 100 nm, which is sufficient for our application. Furthermore, IFVD method is simpler and does not cause any surface damage. Hence, it is utilized in our subsequent fabrication discussed in Chapter 8.

8

Demonstration of Photonic Integrated Devices

In Chapter 6 and Chapter 7, we have discussed the dry-etching process and the quantum well intermixing process, respectively that are important to the fabrication of monolithic integrated devices. In this final chapter, we demonstrate some simple integrated devices, which involve the integration of only two photonic devices. The devices are: (i) the integration of a single-mesa vertical coupler and a multimode interferometer; and (ii) the integration of multimode interferometer and the electroabsorption switch.

The developed processes, together with the devices, will lay the foundation for the more complex integrated devices. They are discussed in detail in this chapter. The optimization of the performance for the devices is beyond the scope of this thesis, as it could involve a separate project to discuss in detail in this aspect.

8.1 Integration of Single-Mesa Vertical Coupler and Multimode Interferometer

8.1.1 Design of Multimode Interferometer and Single-Mesa Vertical Coupler

A MMI is constructed by a waveguide that can support a large number of waveguide modes, called the MMI body, together with a number of narrower waveguides attached to its beginning and its end, which are denoted as input ports and output ports, respectively. The device is an $N \times M$ MMI, where N is the number of input ports, and M is the number of output ports. The input light is launched into the MMI body through one of the input ports and is then distributed among the output ports in a certain pattern after the self-imaging (interference) process. Self-imaging is defined as the property of a multimode waveguide by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation distance [67].

In our application, we are looking at a MMI splitter, in which the signal from an input fiber is split equally among the output ports. For simplicity, we are designing a 1×2 MMI. In order to maintain the compactness of the integration device, we will be utilizing the symmetric restricted interference [139-140] that occurs in the MMI body. This phenomenon happens when the only input port is located at the centre of the MMI body, and hence, only the even modes are excited. This produces a MMI body having a length much less than the other possible MMI designs. However, as a rule of thumb, to produce a well-balanced splitting, the MMI body must be able to support at least $M+1$ modes, where M is the number of output ports.

In this subsection, we present a design of the 1×2 MMI by using the 3-D FDBPM. For our integration, we use a vertical coupler structure similar to that presented in Chapter 3, which is summarized in Table 8.1. The material bandgap of the top

waveguide core is designed with slightly shorter wavelength to reduce the material absorption at the operating wavelength of 1.55 μm . The layers are all undoped since it is an all-passive device. The wafer is grown by DenseLight Semiconductors Singapore. We have carried out the PL measurement on the wafer, and the spectrum is shown in Fig. 8.1. From the result, we can clearly see the two intensity peaks corresponding to the two waveguide cores. The PL is done at 77K, and from our previous experience, the bandgap at 77K is usually about 100 nm less than that at the room temperature. From the spectrum, we can see that for both waveguide cores, the peak wavelengths are quite near to the design values; hence, we can proceed on to use the wafer for our fabrication.

Table 8.1: Layer structure for the SMVC and MMI integrated device

Layer No	Layer	Thickness (μm)
4	InP	1.5
3	$\text{In}_{0.62}\text{Ga}_{0.38}\text{As}_{0.82}\text{P}_{0.18}$ ($\lambda=1.48 \mu\text{m}$, $n=3.4739$)	0.6
2	InP	0.3
1	$\text{In}_{0.70}\text{Ga}_{0.30}\text{As}_{0.65}\text{P}_{0.35}$ ($\lambda=1.33 \mu\text{m}$, $n=3.4000$)	0.7
	InP S-doped substrate	-

Fig. 8.1. PL spectrum of the epitaxy wafer with the SMVC layer structure. The PL is done at 77K to reduce the background noise.

The MMI is fabricated in the top waveguide layer with a body width, W of 8 μm , and with the input and output ports of 2 μm width, as shown in the MMI schematic in

Fig. 8.2. To collect the 2-fold image, the output ports are placed symmetrically about the centre of the MMI, with a separation of $4\ \mu\text{m}$.

Fig. 8.2. Schematic of the 1×2 MMI, showing the various dimension of the MMI and the location of the ports. The SMVC is assumed to be attached to the input port.

From the simulation, it is found that the MMI body is about $69\ \mu\text{m}$ long, which coincides with the MMI length calculated from Eq. (8.1) [67],

$$L = \frac{p}{M} \left(\frac{3}{4} L_{\pi} \right) \quad (8.1)$$

where p is the number of repetition for the self-imaging process, and L_{π} is the beat length, which is defined as

$$L_{\pi} = \frac{4n_r W_e^2}{3\lambda} \quad (8.2)$$

where n_r is the effective index, W_e is the MMI effective width, which is the same as the MMI physical width for HIC structure, and λ is the operating wavelength. The simulation results are shown in Fig. 8.3. The device lengths for the TE and TM polarizations are almost identical because the MMI in nature is relatively polarization insensitive. Besides the 2-fold image, the 3-fold, 4-fold images can also be clearly seen from the plots.

Fig. 8.3. Simulation results for the 1×2 MMI for TE and TM polarizations. The intensity contours are taken at the centre of the top waveguide core, $1.8 \mu\text{m}$ from the top of the structure.

For the design of SMVC, the same procedure as described in Chapter 3 is applied, and hence, it is not elaborated in detail here. The initial waveguide for providing the loading effect of the underlying waveguide is found to be $1 \mu\text{m}$ wide, while the final taper width is $1.3 \mu\text{m}$, expanded over a transfer (taper) length of $150 \mu\text{m}$. The transfer efficiencies of the TE and TM polarizations are found to be 88% and 89%, respectively. The simulation results for the whole structure are shown in Fig. 8.4, in which we show the contour plots of the mode intensity profiles over a plane parallel to the centre of the top waveguide core. The results clearly show that the integrated device is able to perform as desired, in which the light is transferred up to the top waveguide by the SMVC and split equally by the MMI.

Fig. 8.4. Simulation results of the integrated device of SMVC and 1×2 MMI for TE and TM polarizations. The contour plots are obtained at a horizontal plane parallel to the centre of the top waveguide core.

It is found that for the SMVC, the transfer efficiency is sensitive to the final taper width. In Fig. 8.5, we show the transfer efficiencies of the SMVC at different final taper width. We can see that although the transfer efficiencies for both polarizations at the final taper width of 1.3 μm are almost identical, the tolerance against deviation of width is not satisfying. The transfer efficiency will reduce drastically when the final width is less than 1.3 μm . Hence, in the actual fabrication, the final taper width is designed to be 1.4 μm , such that the SMVC is able to have better toleration than with the width of 1.3 μm . Also, the wider the taper width, the easier is the fabrication. This is done at the expense of having some imbalance in the transfer efficiencies for TE and TM polarizations.

Fig. 8.5. Transfer efficiency of the SMVC for different final taper widths for TE and TM polarizations.

8.1.2 Fabrication Results and Discussions

The fabrication of the SMVC is similar to the HIC waveguides we fabricated before. This is because of our new design with single mesa structure, which requires no critical alignment between the two vertically stacked waveguides. Hence, the fabrication process is much simplified. The SEM snapshot of the fabricated device is shown in Fig. 8.6. It is found that possibly due to the photolithography skill and machine capability, the dimension of the devices is larger than the designed values. The deviation of dimension is probably not critical for the MMI, as MMI is a robust device and allows larger fabrication tolerances. However, for the vertical coupler, this is not the case. As presented in Fig. 8.5, the deviation in the taper width could deteriorate the device performance drastically. Moreover, from Fig. 8.1, we also see that the actual PL wavelengths of the wafer are not exactly the same as the designed values; hence, the material indexes may be somewhat different from the design values. All these affect the performance of the vertical coupler. However, the exact deviations of these parameters are difficult to be known, since our SEM resolution is in micron scale and the actual material indexes can only be estimated. Nevertheless, all these could be compensated by tuning the operating wavelength of the device.

Fig. 8.6. SEM photographs showing (a) the 1×2 MMI, (b) the output waveguides of the MMI after the S-bend to ensure some separation ($\sim 50 \mu\text{m}$) between the two waveguide modes on the infrared camera, and (c) part of the taper waveguide. There is some dirt observable in (a) since the SEM system is not located in the cleanroom.

By tuning the operating wavelength, the intersection of the effective index curves (like those previously shown in Chapter 3) can be tuned, and therefore the phase matching condition could be adjusted to fit within the taper region. For our tunable laser, the tuning range is 1510-1630 nm. It is found that at the operating wavelength of about 1530 nm, the performance of the vertical coupler is the best. The mode profile of the output from the rib waveguide (i.e., the top waveguide is uniform with a width of $1 \mu\text{m}$) is shown in Fig. 8.7(a), where we can see that the mode profile is relatively larger. The mode profile shows a tail at the top, which is a typical mode

shape for a rib waveguide. In the tapered top waveguide, the mode profile is smaller and dimmer, as shown in Fig. 8.7(b).

Fig. 8.7. Measured output mode profiles from (a) underlying rib waveguide, (b) single-mesa vertical coupler, and (c) integrated device of SMVC and 1×2 MMI

In one of the devices, the output power directly from the underlying waveguide is about $32 \mu\text{W}$, and from the vertical coupler is about $5.8 \mu\text{W}$, all with an input power of about $700 \mu\text{W}$. These give insertion losses of about 13 dB and 21 dB for the underlying waveguide and vertical coupler, respectively. The device lengths are about 2 mm. From our measurement of the propagation loss of the underlying waveguide, the propagation loss is about 0.4 dB/cm. This is the lowest propagation loss we have ever obtained. This is probably because in the rib structure, there is much less light scattering at the waveguide sidewall. If the propagation loss at the short underlying waveguide is negligible, then the fiber coupling loss is about 13 dB, which includes

the facet reflection loss. With this, we can estimate that the transfer loss and the propagation loss in the top waveguide is about 8 dB. We can also estimate that the minimum transfer efficiency we could achieve is around 20%.

In Fig. 8.7(c), we show the output mode profiles from the 1×2 MMI. The imbalance in the mode intensities is due to the slight imperfection of the cleaving at the output facet. The output powers of the two ports are 4.1 μW and 4.3 μW , respectively, which gives a splitting ratio of almost 50:50 and an insertion loss of about 19 dB, for a given input power of 700 μW . This insertion loss is comparable to the MMI with wider waveguides that we presented before, which is supposed to have lower loss. This implies that the fiber coupling loss has been improved by the use of the single-mesa vertical coupler, compared with an MMI without the SMVC. The reduction in the fiber coupling loss is calculated to be about 8.5 dB (from 15 dB for coupling to the 2 μm top waveguide only, to 6.5 dB for coupling to the SMVC), which is greater than the transfer loss and the propagation loss in the top tapered waveguide. This shows that the integrated SMVC has served its purpose and is effective in reducing overall insertion loss. Although the SMVC is relatively simple to fabricate, further improvement will require optimizing the fabrication of the vertical coupler especially the final taper width. In summary, we have successfully demonstrated, for the first time, the integration of the single-mesa vertical coupler with a passive MMI.

Next, we present the integration of MMI with EA switch that involves more complicated fabrication processes.

8.2 Integration of Multimode Interferometer and Electroabsorption Modulators

8.2.1 Fabrication of MMI and EAM

In this subsection, we demonstrate integration of a MMI and EA modulators to form a 1×2 optical signal switch or controller. The fabrication of the device is relatively complicated, as it involves a passive device (MMI) and several active devices (EAM), which require different material bandgaps and need to be electrically isolated. Hence, it requires some consideration in order to minimize the process steps. The implemented fabrication steps are illustrated in Fig. 8.8. The process flow has been simplified and the details in each step are not presented.

As a first step in the fabrication process, the passive and active regions are defined by IFVD QWI. 200 nm thick PECVD SiO_2 layer is deposited on top of the samples, and then patterned by photolithography and RIE. The photomask contains shapes that protect the passive region, where intermixing is required (i.e., the MMI and the waveguide area), while exposing the active region (i.e., the EA switch region), where the bandgap is to remain. Next, the RIE is used to etch the exposed SiO_2 so that during the subsequent annealing, these regions are not intermixed. All the recipes used are the same as those presented in Chapter 6. The samples are annealed at 700°C for 120s in the RTP to induce the intermixing.

Fig. 8.8. Process flow of the MMI and EAM integrated device

After the intermixing is done, the electrical isolation trenches are defined. They are defined in the same way as the intermixing step, just that the photomask patterns are different. The trenches are 10 μm wide, and are etched no more than 1 μm deep. The purpose is to create isolation between the active and passive regions by etching through the highly-doped layers, such that the electrical leakage is minimized. The trenches need not be too deep as to affect the light propagation in the waveguide core underneath. Fig. 8.9 shows the SEM photographs of the isolation trenches, as well as some other regions on the sample.

Fig. 8.9. SEMs showing (a) the isolation trench that separates the active and passive regions, and (b) cross sectional view of the trench.

In Fig. 8.9, we also see some part of the waveguide structure of a MMI, which is created in the next step. The MMI has a port width of 8 μm , and MMI body width and length of 32 μm and 1150 μm , respectively. The MMIs are etched by using the ICP recipe optimized in Chapter 6, with SiO_2 as etch mask. The etch depth is about 3 μm , which etches through the waveguide core in order to create a ridge structure. The definition of the MMIs is followed by the passivation [141-142] by depositing SiO_2 thin film on the whole structure, which includes the waveguide sidewall. To achieve proper passivation, the deposition has to be conformal, and it is achieved with PECVD, where the SiO_2 layer is deposited from gas sources under relatively high process pressure. An example of the deposition profile is shown in Fig. 8.10, where we can

see that a thin uniform SiO_2 layer is deposited around the sidewall of the waveguides. The SiO_2 thickness for passivation is around 400 nm. The slightly thicker SiO_2 at the corners could be due to the field-enhanced effect at those areas during the plasma deposition.

Fig. 8.10. SEM of the mesa structure for MMI waveguide, covered with a layer of conformal SiO_2 passivation layer deposited by PECVD.

Since the whole structure is now covered with a layer of SiO_2 , windows must be opened to enable electrical contacts with the device underneath. This is done by another round of photolithography and SiO_2 etching to open up a window just on top of the EAM, exposing the InGaAs contact layer. Fig. 8.11 shows a top view of the sample after this step, taken by a high resolution microscope. The figure also shows the pattern of a P-electrode pad, which is defined by the fourth round of photolithography. The SiO_2 layer (blue color region) is under the electrode contact pad to avoid short-circuiting with the substrate, which is connected to the N-electrode. The rest of the region is covered with photoresist (pink color region), except that the top of the waveguide is exposed.

Fig. 8.11. Top view of the electrical P-contact of the device before the metal deposition

Subsequently, the P-electrode metal is deposited by Electron Beam Evaporator on the whole sample surface, and then the photoresist underneath is washed away with acetone, which leaves behind the electrodes that are deposited not on top of the photoresist. This technique is called lift-off. To achieve successful lift-off, the sacrificial layer—photoresist must have undercut sidewalls, and the thickness should be at least five times thicker than the intended layer. Under normal circumstances, positive photoresist sidewalls are overcut, and this causes the metal to be deposited on the positive slope, which complicates the lift-off process and produces irregular metal sidewall. This scenario is shown in Fig. 8.12(a). With our positive photoresist—AZ-5214e, however, the image reversal process can be used to create the undercut profiles. The process steps are shown in Fig. 8.12(b), where we see that a positive photoresist is changed to a negative photoresist, and undercut profiles is obtained. The usual overcut sidewall and the undercut sidewall obtained by us are shown in Fig. 8.12(c) and (d), respectively. Also, in the lift-off process, the photoresist is spin-coated at a lower speed (3 krpm) to increase the thickness to about 2 μm for easier lift-off. For our usual photolithography, the photoresist is about 1.35 μm thick at a spin speed of 5 krpm for the same spinning duration of 35s.

Fig. 8.12. Illustration of process flows for lift-off technique using (a) positive photoresist, and (b) AZ-5214e with image reversal method, which produces the undercut profile beneficial for lift-off process.

For the metal deposition, an Edwards Auto 306 electron-beam evaporator is used. The machine is a vacuum coater equipped with turbo pumping system. The metal used for the P-electrode is gold (Au) with a thickness of 250 nm. Due to its poor adhesion on InGaAs, 50 nm thick of titanium (Ti) is deposited in between the gold and the InGaAs, which acts as an adhesion promoter. The SEM photograph of the completed P-electrodes is shown in Fig. 8.13(a). The contact pads are designed to be $150 \times 150 \mu\text{m}^2$. The cross-sectional view of the active waveguide is shown in Fig. 8.13(b), where we can see the top layer of the waveguide is in direct contact with the electrode, while the substrate is insulated from the P-electrode by the SiO_2 layer.

Fig. 8.13. (a) SEM of the P-electrodes. The electrodes are deposited directly on top of the EAM waveguides, where the InGaAs layer is exposed, as shown in (b) the cross-sectional view of the active waveguide. The square contact pads in (a) are created for easier probing during the measurement stage. Other areas are still covered with passivation SiO_2 .

Throughout all the previous fabrication steps, the alignment of the various layers is very important. To achieve good alignment, alignment markers are incorporated into the photomask design. The alignment markers are located at the two ends of the EAM, and also on the both left and right side of the EAM. There are a total of four alignment markers for an integrated device. In all the photolithography steps, the alignment markers are clearly visible under the microscope of the mask aligner. This

makes the alignments relatively simple. The SEM photograph of the alignment markers is shown in Fig. 8.14.

Fig. 8.14. SEM of two of the alignment markers

After the P-electrodes are deposited, the samples are thinned down to about 100 μm from the original thickness of 350 μm for easier cleaving. The samples are lapped by using solution mixed with alumina (Al_2O_3) powder of 9 μm particle size. After the samples have been thinned down, the N-electrode is then deposited on the back of the substrate. The electrode layers are nickel-germanium-gold-nickel-gold with thicknesses of 5-25-100-20-250 nm, where the nickel is the immediate layer in contact with the substrate. The electrode is deposited all over the surface and no patterning is required. The samples are then annealed at 430°C for 1 minute by using the RTP. The completed devices are presented in Fig. 8.15. Finally, the samples are cleaved and measured, and the discussions are presented in the next subsection.

Fig. 8.15. SEM of the completed integrated devices of MMI and EAM.

8.2.2 Results and Discussions

In the measurement of the integrated device, the same setup as the previous measurement is used. Since the working principle of the switches is based on the electroabsorption effect, the absorption spectra of the device need to be investigated. However, due to the very thin MQW region, the absorption spectra are difficult to be obtained. The photocurrent spectra of the fabricated MQW device when an incident light is coupled into the waveguide are shown in Fig. 8.16. The higher the absorption of the material, the higher the photocurrent generated. Hence, the graph can be used as indication of the absorption spectra of the device [143-144]. From the figure, we can see that at higher wavelength (>1540 nm), the absorption of the material reduces, which is expected as the operating wavelength is getting farther from the active material bandgap. At shorter operating wavelength, it is found that the absorption difference under different bias voltages is higher. Hence, it is interesting to look at the performance of the device within this region.

Fig. 8.16. Photocurrent (absorption) spectra of the fabricated MQW EA switch as a function of input optical wavelength with external reverse bias voltages of 0-5 V.

The extinction ratio characteristics of the integrated device for an incident light wavelength of $1.53\ \mu\text{m}$ are shown in Fig. 8.17. It is obtained by measuring the output intensity at one of the MMI output ports, with a free space polarizer inserted right in front of the detector to separate the different polarizations. The total length of the device is 4 mm, of which about 1 mm is the length of the modulator. The total insertion loss is about 31 dB, including the fiber coupling loss, reflection loss, MMI loss and the background absorption loss in the modulator. In addition, there may be significant loss at the isolation region if the isolation trench is over-etched. The output field profile for the particular port at some of the bias voltages are shown in the insets. The waveguide mode is hard to determine as there is significant stray light nearby, hence the accurate measurement of the extinction ratio of the guided mode is difficult. A possible reason for the stray light is scattering from the isolation trench between the passive and active sections of the device (the trench might have been etched too deep). Another reason could be the imbalance in the MMI and the relatively wide waveguide ports ($8\ \mu\text{m}$) used that give rise to a diffuse distribution in the MMI output. The best extinction ratio that we could measure is about 10.5 dB at a reverse bias of

8 V for TE polarization, which is a very poor result for an intensity modulator. The poor extinction is partly related to the presence of only three quantum wells in the modulator structure, which gives a very small confinement factor. This result, however, is not accurate as any stray light that leaks into the detector would degrade the extinction ratio. From the figure, we can also see that the TM polarization is not modulated. Furthermore, there is a slight reduction of TM absorption under the bias. This is probably because the absorption spectrum actually changes differently for the two polarizations under bias condition, and for a typical waveguide intensity modulator, the absorption for TM polarization is usually much smaller than the TE polarization [109].

Fig. 8.17. Extinction ratio of the MMI and EAM integrated device as a function of external reverse bias voltage and polarization, at the operating wavelength of 1530 nm, with the insets showing the optical modes obtained at different voltages.

We have also measured the MMI and the EAM separately. The MMI do not always give a clear waveguide mode as the stray light is quite strong. This indicates that the MMI design may not be optimized and that the input and output waveguide width (8 μm) may be too large. The best waveguide mode is shown in Fig. 8.18, obtained directly from the input port. In summary, the MMI-EAM switch has not

yielded good results, an indication that the process of integration has not been optimized in our trial. In this trial we used 8 μm wide waveguides in order to simplify the multiple alignment steps. Because of this large waveguide width the MMI is quite long, causing the whole device to be very long and the insertion loss very high. For electrical isolation we have used a simple etched trench which may not be optimized, and hence may have a detrimental effect on the guided mode.

Fig. 8.18. Waveguide profile measured directly from the 8 μm MMI input port

Chapter Summary

In this chapter, first of all we have presented the measurement results of a SMVC and 1×2 MMI integrated device, which gives a good splitting ratio of almost 50:50 and an insertion loss of about 21 dB. Based on estimation, the transfer efficiency is at least 20%. As compared to previous results on MMI, the fiber coupling loss has improved. Besides, we discuss in detail the fabrication process of a MMI and EAM integrated device. The relevant SEMs of the fabrication results are also presented. However, the fabricated devices give relatively poor extinction, which is only about 10.5 dB for TE polarization, with a total insertion loss of about 31 dB. Nevertheless, this is probably because the waveguide structure is not optimized for its electroabsorption effect, and the design of MMI and the integration process are still imperfect.

9

Conclusions and Recommendations

This dissertation has focused on a few key building blocks and processes for photonic integration. A number of novel building blocks have been designed and demonstrated theoretically for the first time, and a few of them have been fabricated and characterized. The fabrication processes have been developed to realize a few relatively simple integrated devices. In particular, a room-temperature ICP dry etch process has been developed, and the quantum well intermixing (QWI) process required to modify the material bandgap has been optimized. The integrated devices demonstrated are a single-mesa vertical coupler integrated with an MMI to demonstrate a reduction in the input fiber coupling loss, and a MMI integrated with active electroabsorption devices to demonstrate active-passive integration using the QWI technique.

In the thesis, first of all, we have presented the design of vertical couplers for polarization manipulation, namely the polarization-independent vertical couplers, and the polarization mode splitters. The design makes use of the high-index-contrast InP/InGaAsP ridge waveguide due to its polarization sensitive properties. The polarization-independent VC is able to transfer the light at more than 90% to the top waveguide for both TE and TM polarizations, while the polarization splitting VC is able to provide contrast ratios up to 19 dB between the two polarizations. A single-mesa

vertical coupler is also proposed. The fabrication of the device is much simpler as compared to the conventional double-mesa VC, because it only requires a single round of photolithography and etching processes. The SMVC is also able to transfer the light in polarization-independent fashion, with transfer efficiencies around 90% for both polarizations. With these designs, the advantages of incorporating a VC into an actual device have extended from improving fiber coupling loss and enabling 3-D integration to polarization manipulation.

We also presented a design of lateral mode filter, by utilizing back-to-back taper waveguides, to filter off the higher order modes of a multimode waveguide. The mode filter imposes only a small insertion loss (about 0.02dB) on the fundamental mode while discriminating against all the higher-order modes in the input waveguide. The filtering action for the higher modes is primarily determined by the width and the length of the single-mode waveguide section. The width could range from 0.3 to 0.8 μm , depending on the etch depth (or ridge height), and the length is determined by the required suppression of the first-order TM mode, which has lower loss than the TE mode. The performance of the mode filter is insensitive to the other parameters, such as the input/output waveguide width, the vertical waveguide structure, and the optical wavelength. The tapered ridge waveguide structure is therefore a compact and robust lateral-mode filter which could be cascaded with any single-mode device using multimode waveguides, to ensure single-mode operation of the device.

In the following chapter, we have shown, theoretically, that it is possible to design directional couplers that can split two wavelengths spaced very far apart in a polarization-insensitive manner. We have considered the wavelength components around 1.3 μm and 1.5 μm regions, where this type of CWDM filter is potentially of great interest to passive optical networks (PON) technology. Although the design principle, based on matching the orders of coupling length, is well known, no feasible theoretical and practical designs have been demonstrated so far, primarily because

they have been based on conventional weakly guiding waveguides. In this thesis, we show that in principle, polarization-independent dual wavelength splitters can be realized in both InP- and Si-based material systems using high-index contrast waveguides. The key is to exploit the highly polarization dependent feature of strongly confined ridge waveguides. Only these waveguides make possible directional couplers with coupling lengths that span over the large range required to achieve polarization-independent wavelength splitting. The particular design for InP discussed above occurs in the single-mode regime with strong birefringence, where the birefringence (and coupling length) is very sensitive to the wavelength, as well as the waveguide width and other structural parameters. Hence, the fabrication requirement is very stringent, but may be achieved with advanced nanofabrication technology. Furthermore, we have also shown that our design approach can be generalized to the design of very compact polarization mode splitters.

After the designs of the various building blocks for photonic integration, we have moved into the study of the fabrication process for InP/InGaAsP ridge waveguides. Etching of InP material is one of the important processes because it defines the final structure of the devices. Between dry and wet etching, dry etching is more anisotropic and hence, it can provide a better control of the device dimension. We have optimized the CH_4/H_2 , $\text{Cl}_2/\text{CH}_4/\text{H}_2$ and Cl_2/N_2 processes for ICP dry etching of InP under room temperature (unheated stage) by utilizing the Taguchi method. The etch rates produced are reasonable, and good surface quality is obtained. The Cl_2 -based recipe does not require substrate heating and thus can be more cost effective and widely applied. The processes have different properties and are suitable for different applications. The Cl_2/N_2 is able to give the highest etch rate at 2 $\mu\text{m}/\text{min}$ with no polymer formation, but the sidewall is undercut and the etch depth controllability could be a challenge. The $\text{Cl}_2/\text{CH}_4/\text{H}_2$ process generally gives a lower etch rate (~ 800 nm/min) and smoother surface, also with no polymer formation, but requires a high

ICP power. The CH_4/H_2 process produces the lowest etch rate (with possibly polymer contamination), but smoother surface and better structural verticality at a lower ICP power. Lower ICP power is preferable to reduce surface and sidewall damage, moreover, the recipe without chlorine is also safer to use. All processes give very good selectivity against the oxide mask. The selectivity of InP against oxide mask for Cl_2/N_2 process (55:1) is one of the highest reported so far.

Besides the dry etching, quantum well intermixing is another important process to realize monolithic integration. We have studied and compared two of the QWI techniques, namely the argon plasma-enhanced QWI and the impurity-free vacancy-enhanced disordering. The two techniques are able to provide the differential blueshift of up to 80 nm and 100 nm, respectively, with the PE-QWI requires higher annealing temperature at 750°C, which is not preferred. Also, the PE-QWI method tends to sputter away the cap layer, leaving behind a rough surface. Hence, we opt for the IFVD method, which is a much simpler process and do not cause serious surface damage. The optimum annealing temperature is found to be 700°C for duration of 120s, with a SiO_2 cap thickness of 200 nm.

In the final part of the thesis, we have demonstrated the integration of: (i) SMVC and 1×2 MMI, and (ii) 1×2 MMI and EAM. For the SMVC and 1×2 MMI integrated device, the SMVC is able to couple the light from an optical fiber up to the MMI on top of the device. The insertion loss of the whole device is about 21 dB, and the splitting ratio of the MMI is almost 50:50. Next, we show the integration of a 1×2 MMI and EA switches. The fabrication process is complicated as it consists of multiple layers and both active and passive devices. The fabrication process involves QWI, electrical isolation, waveguide etching, wafer lapping and metallization. But nevertheless, the device is fabricated and measured. The extinction ratio is about 10.5 dB for TE polarization, with a total insertion loss of 31 dB. The extinction ratio is relatively poor

because the EA waveguide structure and the fabrication process have not been optimized.

As recommendation for improvement, the wafer structure is to be modified and optimized to achieve an improved device performance, in terms of the extinction ratio and the insertion loss. The wafer, which was obtained from IMRE, was designed as a laser structure with only three quantum wells. For EA modulator application, it is better to have more quantum wells so as to have higher absorption and also stronger waveguide confinement. Besides, the waveguide width would have to be modified. On the one hand, wider waveguide minimizes the sidewall scattering effect, on the other hand, narrower waveguide reduces the overall device length. Currently, the large waveguide width is used to make the multi-step fabrication easier. With better fabrication control, it should be possible to reduce the waveguide width to, say, 3 μm . The MMI width and length would then be much reduced. Other than these, the number of channels for the MMI can also be increased. This applies to the SMVC and MMI integrated device as well. In addition, it could be further integrated with other active devices, such as a photodetector or an EAM, attached after the MMI.

Author's Publications

Journals/Letters:

First Author

1. C.-W. Lee, M.-K. Chin, Design of vertical polarization mode splitter with mode-size transformer," *Photonics Technology Letters*, vol. 16, pp. 2069-2071, 2004.
2. C.-W. Lee, M. K. Chin, M. K. Iyer, and A. Popov, "Asymmetric waveguides vertical couplers for polarization-independent coupling and polarization-mode splitting," *J. Lightwave Technol.* vol. 23, No. 4, pp. 1818-1827, Apr. 2005.
3. C.-W. Lee, M.-K. Chin, "Design of lateral-modes filter based on high-index contrast waveguide," *Optics Communications*, vol. 253, pp. 87-94, 2005.
4. C.-W. Lee, D. Nie, T. Mei, M.-K. Chin, "Study and optimization of room temperature inductively coupled plasma etching of InP using $\text{Cl}_2/\text{CH}_4/\text{H}_2$ and CH_4/H_2 ," *J. Crystal Growth*, vol. 288, pp. 213-216, 2006.
5. C.-W. Lee, M.-K. Chin, "Room-temperature inductively coupled plasma etching of InP using Cl_2/N_2 and $\text{Cl}_2/\text{CH}_4/\text{H}_2$," *Chinese Physics Letter*, vol. 23, pp. 903-906, 2006.

Co-author

6. M.-K. Chin, C.-W. Lee, Jinyuan Shen, "Polarization-independent vertical coupler for photonics integration," *Optics Express*, vol. 12, pp. 117-123, 2004.
7. S. Y. Lee, S. Darmawan, C.-W. Lee and M.-K. Chin, "Transformation between directional couplers and multi-mode interferometers based on ridge waveguides," *Optics Express*, vol. 12, pp. 3079-3085, 2004.

8. S. Darmawan, S. Y. Lee, C.-W. Lee and M.-K. Chin, "Transformation of directional couplers to multi-mode interferometers based on ridge waveguides and its application," *Journal of Nonlinear Optical Physics Materials*, vol. 14, No. 2, pp. 221-235, 2005.
9. S. Darmawan, S. Y. Lee, C.-W. Lee, and M. K. Chin, "A rigorous comparative analysis of directional couplers and multimode interferometers based on ridge waveguides," *IEEE J. Sel. Top. In Quantum Electron.* Vol 11, No. 2, pp. 466-475, 2005.
10. M. K. Chin, C.-W. Lee, S. Y. Lee, S. Darmawan, "High Index Contrast Waveguides and Devices," *Applied Optics* vol. 44, No. 15, pp. 3077-3086, 2005.

Conference Proceedings:

11. C.-W. Lee, M. K. Chin, "Design of polarization filter based on vertical coupler," in *Integrated Photonics Research and Applications (IPRA)*, San Francisco, U.S.A., pap. IFC4, June 30-July 2, 2004.
12. C.-W. Lee, M.-K. Chin, "Higher order lateral-modes discrimination in ridge waveguides for photonic integrated circuits," *Photonics Asia*, Beijing, China, Oct 8-12, 2004. (Invited paper)
13. C.-W. Lee, M.-K. Chin, "Vertical coupler architecture for polarization-independent coupling and polarization-selective coupling," *Photonics Asia*, Beijing, China, Oct 8-12, 2004.
14. C. W. Lee, S. Darmawan, S. Y. Lee, and M. K. Chin, "Design of Polarization-independent Wavelength Splitter based on Single Conventional Directional Coupler," in *Integrated Photonics Research and Applications (IPRA)*, San Diego, U.S.A., pap. IMG2, April 11-13, 2005.

15. C.-W. Lee, D. Nie, T. Mei, R. Akkipeddi, M. K. Chin, "Taguchi optimization of Inductively Coupled Plasma etching of InP using CH₄/H₂ and Cl₂/CH₄/H₂ under room temperature," *International Conf. on Materials for Advanced Applications* (ICMAT), Singapore, pap. MA-6-OR31, July 4-8, 2005.
16. C.-W. Lee, S.-Y. Lee, M.-K. Chin, "Design of a Single Mesa Vertical Coupler," *Photonics North'06*, Quebec City, Canada, pap. GW-05-4-3, June 5-8, 2006.

References

1. H. Yong, Y.-H. Kuo, S. Xu, A. Liu, R. Jones, Mario, O. Cohen, O. Rada, "Monolithic integrated Raman silicon laser," *Optics Express*, vol. 14, pp. 6705-6712, 2006.
2. H. Rong, "A continuous-wave Raman silicon laser," *Nature*, vol. 433, pp. 725-728, 2005.
3. S. G. Cloutier, P. A. Kossyrev, J. Xu, "Optical gain & stimulated emission in periodic nanopatterned crystalline silicon," *Nature Materials*, vol. 4, pp. 887 (2005).
4. L. Pavesi, L. Dal Negro, C. Mazzoleni, G. Franzò, F. Priolo, "Optical gain in silicon nanocrystals," *Nature*, vol. 408, pp. 440-444, 2000.
5. O. Boyraz, B. Jalali, "Demonstration of a silicon Raman laser," *Optics Express*, vol. 12, pp. 5269-5273, 2004.
6. R. Espinola, J. Dadap, R. Osgood, Jr., S. McNab, Y. Vlasov, "Raman amplification in ultrasmall silicon-on-insulator wire waveguides," *Optics Express*, vol. 12, pp. 3713-3718, 2004.
7. D. Hofstetter, B. Maisenhölder, H. P. Zappe. "Quantum-well intermixing for fabrication of laser and photonics integrated circuits," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 794-802, 1998.
8. S. D. McDougall, O. P. Kowalski, C. J. Hamilton, F. Camacho, B. Qiu, M. Ke, R. M. De La Rue, A. C. Bryce, J. H. Marsh, "Monolithic integration via a universal damage enhanced quantum-well intermixing technique," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 636-646, 1998.
9. H. S. Djie, T. Mei, J. Arokiaraj, C. Sookdhis, S. Y. Yu, L. K. Ang, X. H. Tang, "Experimental and theoretical analysis of argon plasma-enhanced quantum-well intermixing," *IEEE Journal of Quantum Electronics*, vol. 40, pp. 166-174, 2004.

10. J. P. Reithmaier, A. Forchel, "Focused ion-beam implantation induced thermal quantum-well intermixing for monolithic optoelectronic device integration," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 595-605, 1998.
11. H.-S. Kim, J. W. Park, D. K. Oh, K. R. Oh, S. J. Kim, I.-H. Choi, "Quantum well intermixing of $\text{In}_{1-x}\text{Ga}_x\text{As}/\text{InP}$ and $\text{In}_{1-x}\text{Ga}_x\text{As}/\text{In}_{1-x}\text{Ga}_x\text{As}_{1-y}\text{P}_y$ multiple-quantum-well structures by using the impurity-free vacancy diffusion technique," *Semiconductor Science and Technology*, vol. 15, pp. 1005-1009, 2000.
12. M. K. Chin, "Polarization dependence in waveguide-coupled micro-resonators," *Optics Express*, vol. 11, pp. 1724-1730, 2003.
13. Y. Shani, C. H. Henry, R. C. Kistler, R. F. Kazarinov, K. J. Orlowsky, "Integrated optics adiabatic devices on silicon," *IEEE Journal of Quantum Electronics*, vol. 27, pp. 556 – 566, 1991.
14. H. Kawata, T. Ogawa, N. Yoshimoto, "Multi-channel video and IP signal multiplexing system using CWDM technology," *IEEE Journal of Lightwave Technologies*, vol. 22, pp. 1454-1462, 2004.
15. K. Kato, Y. Tohmori, "PLC hybrid integration technology and its application to photonic components," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, pp. 4-13, 2000.
16. K. Kawano, M. Kohtoku, M. Wada, H. Okamoto, Y. Itaya, "Design of a spot-size-converter-integrated laser diode (SS-LD) with a lateral taper, thin-film core and ridge in the 1.3 μm -wavelength region based on the 3-D BPM," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 2, pp. 348-354, 1996.
17. Y. Inaba, M. Kito, T. Nishikawa, M. Ishino, Y. Matsui, "Multi-quantum-well lasers with tapered active stripe for direct coupling to single-mode fiber," *IEEE Photonics Technology Letters*, vol. 9, pp. 722-724, 1997.

18. V. Vusirikala, S. S. Saini, R. E. Bartolo, S. Agarwala, R. D. Whaley, F. G. Johnson, D. R. Stone, and M. Dagenais, "1.55- μm InGaAsP-InP laser arrays with integrated-mode expanders fabricated using a single epitaxial growth," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp.1332-1343, 1997.
19. R. Y. Fang, D. Bertone, M. Melinga, I. Montrosset, G. Oliveti, R. Paoletti, "Low-cost 1.55- μm InGaAsP-InP spot-size-converter (SSC) laser with conventional active layers," *IEEE Photonics Technology Letters*, vol. 9, pp. 1084-1086, 1997.
20. K. Kawano, M. Kohtoku, H. Okamoto, Y. Itaya, M. Naganuma, "Coupling and conversion characteristics of spot-size-converter integrated laser diodes," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 1351-1360, 1997.
21. Y. Kawamura, K. Wakita, Y. Yoshikuni, Y. Itaya, and H. Asahi, "Monolithic integration of a DFB laser and an MQW optical modulator in the 1.5 μm wavelength range," *IEEE Journal of Quantum Electronics*, vol. QE-23, pp. 915-918, 1987.
22. H. Soda, M. Furutsu, K. Sato, N. Okazaki, Y. Yamazaki, H. Nishimoto, H. Ishikawa, "High-power and high-speed semi-insulating BH structure monolithic electroabsorption modulator/DFB laser light source," *Electronics Letters*, vol. 26, pp. 9-10, 1990.
23. B. Mason, G. A. Fish, S. P. DenBaars, L. A. Coldren, "Widely tunable sampled grating DBR laser with integrated electroabsorption modulator," *IEEE Photonics Technology Letters*, vol. 11, pp. 638-640, 1999.
24. J. E. Johnson, L. J.-P. Ketelsen, J. A. Grenko, S. K. Sputz, J. Vandenberg, M. W. Focht, D. V. Stampone, L. J. Peticolas, L. E. Smith, K. G. Glogovsky, G. J. Przybylek, S. N. G. Chu, J. L. Lentz, N. N. Tzafaras, L. C. Luther, T. L. Pernell, F. S. Walters, D. M. Romero, J. M. Freund, C. L. Reynolds, L. A. Gruezeke, R. People, M. A. Alam, "Monolithically integrated semiconductor optical amplifier and

-
- electroabsorption modulator with dual-waveguide spot-size converter input," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, pp. 19-25, 2000.
25. B. Mason, J. Barton, G. A. Fish, L. A. Coldren, S. P. DenBaars, "Design of sampled grating DBR lasers with integrated semiconductor optical amplifiers," *IEEE Photonics Technology Letters*, vol. 14, pp. 1457-1459, 2002.
  26. M. G. Young, U. Koren, B. I. Miller, M. A. Newkirk, M. Chien, M. Zirngibl, C. Dragone, B. Tell, H. M. Presby, G. Raybon, "A 16×1 wavelength division multiplexer with integrated distributed Bragg reflector lasers and electroabsorption modulators," *IEEE Photonics Technology Letters*, vol. 5, pp. 908–910, 1993.
  27. K. Kudo, K. Yashiki, T. Sasaki, T. Y. Yokoyama, K. Hamamoto, T. Morimoto, and M. Yamaguchi, "1.55-μm wavelength-selectable microarray DFB-LDs with monolithically integrated MMI combiner, SOA, and EA-modulator," *IEEE Photonics Technology Letters*, vol. 12, pp. 242–244, 2000.
  28. R. Nagarajan, C. H. Joyner, R. P. Schneider, Jr., J. S. Bostak, T. Butrie, A. G. Dentai, V. G. Dominic, P. W. Evans, M. Kato, M. Kauffman, D. J. H. Lambert, S. K. Mathis, A. Mathur, R. H. Miles, M. L. Mitchell, M. J. Missey, S. Murthy, A. C. Nilsson, F. H. Peters, S. C. Pennypacker, J. L. Pleumeekers, R. A. Salvatore, R. K. Schlenker, R. B. Taylor, H.-S. Tsai, M. F. Van Leeuwen, J. Webjorn, M. Ziari, D. Perkins, J. Singh, S. G. Grubb, M. S. Reffle, D. G. Mehuys, F. A. Kish, D. F. Welch, "Large-scale photonic integrated circuits," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 11, pp. 50-65, 2005.
  29. R. Nagarajan, M. Kato, V. G. Dominic, C. H. Joyner, R. P. Schneider, Jr., A. G. Dentai, T. Desikan, P. W. Evans, M. Kauffman, D. J. H. Lambert, S. K. Mathis, A. Mathur, M. L. Mitchell, M. J. Missey, S. Murthy, A. C. Nilsson, F. H. Peters, J. L. Pleumeekers, R. A. Salvatore, R. B. Taylor, M. F. Van Leeuwen, J. Webjorn, M. Ziari, S. G. Grubb, D. Perkins, M. Reffle, D. G. Mehuys, F. A. Kish, D. F. Welch,
-

-
- “400 Gbit/s (10 channel×40Gbit/s) DWDM photonic integrated circuits,” *Electronics Letters*, vol. 41, 2005.
30. R. Nagarajan, M. Kato, J. L. Pleumeekers, P. Evans, D. Lambert, A. Chen, V. Dominic, A. Mathur, P. Chavarkar, M. Missey, A. Dentai, S. Hurtt, J. Bäck, R. Muthiah, S. Murthy, R. Salvatore, S. Grubb, C. Joyner, J. Rossi, R. Schneider, M. Ziari, F. Kish, D. Welch, “Single-chip 40-channel InP transmitter photonic integrated circuit capable of aggregate data rate of 1.6 Tbit/s,” *Electronics Letters*, vol. 42, 2006.
  31. S.-S. Lee, S.-Y. Shin, “Polarisation-insensitive digital optical switch using anelectro-optic polymer rib waveguide,” *Electronics Letters*, vol. 33, pp. 314-316, 1997.
  32. I. Kiyat, A. Aydinli, N. Dagli, “High-Q silicon-on-insulator optical rib waveguide racetrack resonators,” *Optics Express*, vol. 13, pp. 1900-1905, 2005.
<http://www.opticsinfobase.org/abstract.cfm?URI=oe-13-6-1900>
  33. T. Yuasa, K. Onabe, Y. Ide, Y. Isoda, J. Hayashi, T. Furuse, I. Sakume, “1.3 μm InGaAsP/InP buried rib waveguide lasers,” *Journal of Applied Physics*, vol. 54, pp. 50-56, 1983.
  34. A. Carenco, L. Menigaux, Ph. Delpech, “Multiwavelength GaAs rib waveguide directional-coupler switch with ‘stepped $\Delta\beta$ schottky electrodes,” *Journal of Applied Physics*, vol. 50, pp. 5139-5147, 1979.
  35. B. Unal, C.-Y. Tai, D. P. Shepherd, J. S. Wilkinson, N. M. B. Perney, M. C. Netti, G. J. Parker, “Nd:Ta₂O₅ rib waveguide lasers,” *Applied Physics Letters*, vol. 86, pp. 021110-1-3, 2005.
  36. S. D. Roh, T. S. Yeoh, R. B. Swint, A. E. Huber, C. Y. Woo, J. S. Hughes, J. J. Coleman, “Dual-wavelength InGaAs-GaAs ridge waveguide distributed bragg
-

-
- reflector lasers with tunable mode separation," *IEEE Photonics Technology Letters*, vol. 12, pp. 1307-1309, 2000.
37. J.-K. Chen, S.-C. Lee, "AlGaAs/GaAs visible ridge waveguide laser with multicavity structure," *IEEE Journal of Quantum Electronics*, vol. QE-23, pp. 1283-1286, 1987.
  38. J. Kngs, P. Savolainen, M. Toivonen, S. Orsila, P. Corvini, M. Jansen, R. F. Nabiev, M. Pessa, "High-efficiency GaInP-AlGaInP ridge waveguide single-mode lasers operating at 650 nm," *IEEE Photonics Technology Letters*, vol. 10, pp. 1533-1535, 1998.
  39. L. H. Spielman, Y. S. Oei, E. G. Metaal, F. H. Groen, I. Moerman, M. K. Smit, "Extremely small multimode interference couplers and ultrashort bends on InP by deep etching," *IEEE Photonics Technology Letters*, vol. 6, pp. 1008-1010, 1994.
  40. J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, P.-T. Ho, "Higher order filter response in coupled microring resonators," *IEEE Photonics Technology Letters*, vol. 12, pp. 320-322, 2000.
  41. M. K. Chin, C. Youtsey, W. Zhao, T. Pierson, Z. Ren, S. L. Wu, L. Wang, Y. G. Zhao, S. T. Ho, "GaAs microcavity channel-dropping filter based on a race-track resonator," *IEEE Photonics Technology Letters*, vol. 11, pp. 1620-1622, 1999.
  42. K. Kawano, M. Kohtoku, M. Wada, H. Okamoto, Y. Itaya, "Design of a spotsize-converter-integrated laser diode (SS-LD) with a lateral taper, thin-film core and ridge in the 1.3 μm -wavelength region based on the 3-D BPM," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 2, pp. 348-354, 1996.
  43. Y. Inaba, M. Kito, T. Nishikawa, M. Ishino, Y. Matsui, "Multi-quantum-well lasers with tapered active stripe for direct coupling to single-mode fiber," *IEEE Photonics Technology Letters*, vol. 9, pp. 722-724, 1997.
-

-
44. V. Vusirikala, S. S. Saini, R. E. Bartolo, S. Agarwala, R. D. Whaley, F. G. Johnson, D. R. Stone, and M. Dagenais, "1.55- μm InGaAsP-InP laser arrays with integrated-mode expanders fabricated using a single epitaxial growth," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp.1332-1343, 1997.
  45. R. Y. Fang, D. Bertone, M. Melinga, I. Montrosset, G. Oliveti, R. Paoletti, "Low-cost 1.55- μm InGaAsP-InP spot-size-converter (SSC) laser with conventional active layers," *IEEE Photonics Technology Letters*, vol. 9, pp. 1084-1086, 1997.
  46. K. Kawano, M. Kohtoku, H. Okamoto, Y. Itaya, M. Naganuma, "Coupling and conversion characteristics of spot-size-converter integrated laser diodes," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 1351-1360, 1997.
  47. S. S. Agashe, S. Datta, F. Xia, S. R. Forest, "A monolithically integrated long-wavelength balanced photodiode using asymmetric twin-waveguide technology," *IEEE Photonics Technology Letters*, vol. 16, pp. 236-238, 2004.
  48. B. Mersali, A. Ramdane, and A. Carencu, "Optical-mode transformer: a III-V circuit integration enabler," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 1321-1331, 1997.
  49. N. Yoshimoto, K. Kawano, H. Takeuchi, S. Kondo, Y. Noguchi, "Highly efficient coupling semiconductor spot-size converter with an InP/InAlAs multiple-quantum-well core," *Applied Optics*, pp. 1007-1014, 1995.
  50. B. Mersali, H. J. Brückner, M. Feuillede, S. Sainson, A. Ougazzaden, A. Carencu, "Theoretical and experimental studies of a spot-size transformer with integrated waveguide for polarization insensitive optical amplifiers," *IEEE Journal of Lightwave Technology*, vol. 13, pp. 1865-1872, 1995.
  51. B. Liu, A. Shakouri, P. Abraham, Y. J. Chiu, S. Zhang, J. E. Bowers, "Fused InP-GaAs vertical coupler filters," *IEEE Photonics Technology Letters*, vol. 11, pp. 93-95, 1999.
-

52. W. Chi, C. Rolland, F. Shepherd, C. Larocque, N. Puetz, K. D. Chik, J. M. Xu, "InGaAsP/InP vertical directional coupler filter with optimally designed wavelength tunability," *IEEE Photonics Technology Letters*, vol. 4, pp. 457-459, 1993.
53. R. C. Alferness, L. L. Buhl, U. Koren, B. I. Miller, M. G. Young, T. L. Koch, C. A. Burrus, G. Raybon, "Broadly tunable InGaAsP/InP buried rib waveguide vertical coupler filter," *Applied Physics Letters*, vol. 60, pp. 980-982, 1992.
54. M. Raburn, B. Liu, K. Rauscher, Y. Okuno, N. Dagli, J. E. Bowers, "3-D photonics circuits technology," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 935 – 942, 2002.
55. B. Liu, A. Shakouri, P. Abraham, J. E. Bowers, "Optical add/drop multiplexers based on X-crossing vertical coupler filters," *IEEE Photonics Technology Letters*, vol. 12, pp. 410-412, 2000.
56. O. Mitomi, N. Yoshimoto, K. Magari, T. Ito, Y. Kawaguchi, Y. Suzuki, Y. Tohmori, and K. Kasaya, "Analyzing the polarization dependence in optical spot-size converter by using a semi-vectorial finite-element beam propagation method," *IEEE Journal of Lightwave Technology*, vol. 17, pp. 1255-1262, 1999.
57. G. Jin, S. Shi, A. Sharkawy, D. W. Prather, "Polarization effects in tapered dielectric waveguides," *Optics Express*, vol. 11, pp. 1931-1941, 2003.
58. V. M. N. Passaro, F. D. Leonardis, "Design of polarization insensitive vertical couplers in silicon-on-insulator waveguides with small cross section," in *IEEE/LEOS Workshop on Fibres and Optical Passive Components*, Palermo, Italy, June 22-24, 2005.
59. P. Albrecht, M. Hamacher, H. Heidrich, D. Hoffman, H. -P. Nolting, C. M. Weinert, "TE/TM mode splitters on InGaAsP/InP," *IEEE Photonics Technology Letters*, vol. 2, pp. 114-116, 1990.

60. J. J. G. M. van der Tol, J. M. Pedersen, E. G. Metaal, J. J. –W. van Gaalen, Y. S. Oei, F. H. Groen, "A short polarization splitter without metal overlays on InGaAsP-InP," *IEEE Photonics Technology Letters*, vol. 9, pp. 209-211, 1997.
61. M. H. Hu, J. Z. Huang, R. Scarmozzino, M. Levy, and R. M. Osgood Jr., "Tunable Mach-Zehnder polarization splitter using height-tapered Y-branches," *IEEE Photonics Technology Letters*, vol. 9, pp. 773 - 775, 1997.
62. L. B. Soldano, A. H. de Vreede, M. K. Smit, B. H. Verbeek, E. G. Metaal, F. H. Groen, "Mach-Zehnder interferometer polarization splitter in InGaAsP/InP," *IEEE Photonics Technology Letters*, vol. 6, pp. 402-404, 1994.
63. N. Goto, G. L. Yip, "A TE-TM mode splitter in LiNbO₃ by proton exchange and Ti diffusion," *IEEE Journal of Lightwave Technology*, pp. 1567-1573, 1989.
64. Y. Suzuki, H. Iwamura, O. Mikami, "Polarization mode filter in GaAs-AlAs superlattice fabricated by SiO₂ Cap disordering," *IEEE Photonics Technology Letters*, vol. 2, pp. 818-820, 1990.
65. J. J. G. M. van der Tol, J. W. Pedersen, E. G. Metaal, Y. S. Oei, H. van Brug, I. Moerman; "Mode evolution type polarization splitter on InGaAsP/InP", *IEEE Photonics Technology Letters*, vol. 5, pp. 1412 - 1414, 1993.
66. S. M. Garner, V. Chuyanov, S.S. Lee, A. Chen, W.H. Steier, and L. R. Dalton, "Vertically integrated waveguide polarization splitters using polymers", *IEEE Photonics Technology Letters*, vol. 11, pp. 842-844, 1999.
67. L. B. Soldano, E. C. M. Pennings, "Optical multi-mode interference devices based on self-imaging principles and applications," *IEEE Journal of Lightwave Technology*, vol. 13, pp. 615-627, 1995.
68. M. Kohtoku, Y. Shibata, Y. Yoshikumi, "Evaluation of the rejection ratio of an MMI-based higher order mode filter using optical low-coherence reflectometry," *IEEE Photonics Technology Letters*, vol. 14, pp. 968-970, 2002.

-
69. J. Leuthold, R. Hess, J. Eckner, P. A. Besse, H. Melchior, "Spatial mode filters realized with multimode interference couplers," *Optics Letters*, vol. 21, pp. 836-838, 1996.
  70. M. Kobayashi, H. Terui, K. Egashira, "Optical-mode filters using coupling between two nonidentical waveguides," *Applied Optics*, vol. 17, pp. 486-490, 1978.
  71. H. Han, J. J. Coleman, "Lateral-mode discrimination in ridge waveguides by misaligned total internal reflection mirrors," *IEEE Photonics Technology Letters*, vol. 7, pp. 715-717, 1995.
  72. H. Yajima, "Dielectric bypass waveguide mode order converter," *IEEE Journal of Quantum Electronics*, vol. QE-15, pp. 482-487, 1979.
  73. R. N. Thurston, E. Kapon, Y. Silberberg, "Analysis of mode separation in multichannel branching waveguides," *IEEE Journal of Quantum Electronics*, vol. QE-23, pp. 1245-1255, 1987.
  74. W. K. Burns, A. F. Milton, "An analysis solution for mode coupling in optical waveguide branches," *IEEE Journal of Quantum Electronics*, vol. QE-16, pp. 446-454, 1989.
  75. S. Mukai, Y. Kaneko, M. Watanabe, H. Itoh, H. Yajima, "Laser Beam scanning using a local deflector integrated with an effective mode filter," *Applied Physics Letters*, vol. 51, pp. 2091-2093, 1987.
  76. K. Furuya, Y. Suematsu, J. Nayyer, S. Ishikawa, F. Tagami, "External higher-index mode filters for band widening of multimode optical fibers," *Applied Physics Letters*, vol. 27, pp. 456-458, 1975.
  77. T. Ozeki, T. Ito, T. Tamura, "Tapered section of multimode cladded fibers as mode filters and mode analyzers," *Applied Physics Letters*, vol. 26, pp. 386-388, 1975.
-

-
78. Spectral grids for WDM applications: CWDM wavelength grid, Recommendation G.694.2 (12/03), International Telecommunication Union, [Access on: March 24, 2007, Online], <http://www.itu.int/rec/T-REC-G.694.2-200312-I/en>
  79. C. R. Doerr, R. Pafchek, L. W. Stulz, "Integrated band demultiplexer using waveguide grating routers," *IEEE Photonics Technology Letters*, vol. 15, pp. 1088-1090, 2003.
  80. B. J. Offrein, G. L. Bona, F. Horst, W. M. Salemink, R. Beyeler, R. Germann, "Wavelength tunable optical add-after-drop filter with flat passband for WDM networks," *IEEE Photonics Technology Letters*, vol. 11, pp. 239-241, 1999.
  81. R. J. Shul, G. A. Vawter, C. G. Willison, M. M. Bridges, J. W. Lee, S. J. Pearton, C. R. Abernathy, "Comparison of plasma etch technology for III-V nitrides," *Solid-State Electronics*, vol. 42, pp. 2259-2267, 1998.
  82. C.-Y. Park, J.-B. Yoo, C. Park, K.-S. Hyun, D.-K. Oh, Y. H. Lee, C. Lee, H.-M. Park, "Fabrication of InGaAs/InP avalanche photodiodes by reactive ion etching using CH₄/H₂ gases," *Journal of Vacuum Science and Technology B*, vol. 13, pp. 974-977, 1995.
  83. B.-T. Lee, R. A. Logan, R. F. Kalicek, Jr., A. M. Sergent, D. L. Coblentz, K. W. Wecht, T. Tanbun-Ek, "Fabrication of InGaAsP/InP buried heterostructure laser using reactive ion etching and metalorganic chemical vapor deposition," *IEEE Photonics Technology Letters*, vol. 5, pp. 279-281, 1993.
  84. P. D. Swanson, D. B. Shire, C. L. Tang, M. A. Parker, J. S. Kimmet, R. J. Michalak, "Electron-cyclotron resonance etching of mirrors for ridge-guided lasers," *IEEE Photonics Technology Letters*, vol. 7, pp. 605-607, 1995.
  85. S. Park, S.-S. Kim, L. Wang, S.-T. Ho, "InGaAsP-InP nanoscale waveguide-coupled microring lasers with submilliampere threshold current using Cl₂-N₂
-

-
- based high-density plasma etching," *IEEE Journal of Quantum Electronics*, vol. 41, pp. 351-356, 2005.
86. D. G. Rabus, M. Hamacher, U. Troppenz, H. Heidrich, "Optical filters based on ring resonators with integrated semiconductor optical amplifiers in GaInAsP-InP," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 8, pp. 1405-1411, 2002.
87. R. Grover, T. A. Ibrahim, T. N. Ding, Y. Leng, L.-C. Kuo, S. Kanakaraju, K. Amarnath, L. C. Calhoun, P. T. Ho, "Laterally coupled InP based single-mode microracetrack notch filter," *IEEE Photonics Technology Letters*, vol. 15, pp. 1082-1084, 2003.
88. G. Franz, "Reactive ion etching of III/V semiconductors using carbon containing gases," *Journal of Electrochemical Society*, vol. 137, pp. 2896-2903, 1990.
89. T. R. Hayes, M. A. Dreisbach, P. M. Thomas, W. C. Dautremont-Smith, L. A. Heimbrook, "Reactive ion etching of InP using CH₄/H₂ mixtures: mechanisms of etching and anisotropy," *Journal of Vacuum Science and Technology B*, vol. 7, pp. 1130-1139, 1989.
90. C. S. Whelan, T. E. Kazior, K. Y. Hur, "High rate CH₄:H₂ plasma etch processes for InP," *Journal of Vacuum Science and Technology B*, vol. 15, pp. 1728-1732, 1997.
91. H.-Y. Chen, H. E. Ruda, "Inductively coupled plasma etching of InP using CH₄/H₂ and CH₄/H₂/N₂," *Journal of Vacuum Science and Technology B*, vol. 20, pp. 47-52, 2001.
92. J. W. McNabb, H. G. Craighead, H. Temkin, R. A. Logan, "Anisotropic reactive ion etching of InP in methane/hydrogen based plasmas," *Journal of Vacuum Science and Technology B*, vol. 9, pp. 3535-3537, 1991.
-

-
93. J. Werking, L. Schramm, C. Nguyen, E. L. Hu, H. Kroemer, "Methane/hydrogen-based reactive ion etching of InAs, InP, GaAs, and GaSb," *Applied Physics Letter*, vol. 58, pp. 2003-2005, 1991.
  94. K. Asakawa, T. Yoshikawa, S. Kohmoto, Y. Nambu, Y. Sugimoto, "Chlorine-based dry-etching of III-V compound semiconductors for optoelectronic application," *Japanese Journal of Applied Physics*, vol. 37, pp. 373-387, 1998.
  95. J. Lin, A. Leven, N. G. Weimann, Y. Yang, R. F. Kopf, R. Reyes, Y. K. Chen, F.-S. Choa, "Smooth and vertical-sidewall InP etching using Cl_2/N_2 inductively coupled plasma," *Journal of Vacuum Science and Technology B*, vol. 22, pp. 510-512, 2004.
  96. T. Nishibe, S. Nunoue, "Dry etching of InGaAsP/InP structures by reactive ion beam etching using chlorine and argon," *Japanese Journal of Applied Physics*, vol. 29, pp. 2449-2452, 1990.
  97. G. A. Vawter, C. I. H. Ashby, "Reactive-ion-beam etching of InP in a chlorine-hydrogen mixture," *Journal of Vacuum Science and Technology B*, vol. 12, pp. 3374-3377, 1994.
  98. A. Matsutani, H. Ohtsuki, F. Koyama, K. Iga, "Vertical and smooth etching of InP by Cl_2/Xe inductively coupled plasma," *Japanese Journal of Applied Physics*, vol. 38, pp. 4260-4261, 1999.
  99. J. Etrillard, P. Ossart, G. Patriarche, M. Juhel, J. F. Bresse, C. Daguet, "Anisotropic etching of InP with low sidewall and surface induced damage in inductively coupled plasma etching using SiCl_4 ," *Journal of Vacuum Science and Technology A*, vol. 15, pp. 626-632, 1997.
  100. F. Ren, W. S. Hobson, J. R. Lothian, J. Lopata, J. A. Caballero, S. J. Pearton, M. W. Cole, "High rate dry etching of InGaP in BCl_3 plasma chemistries," *Applied Physics Letters*, vol. 67, pp. 2497-2499, 1995.
-

101. H.-Y. Chen, H. E. Ruda, A. Z. Navarro, "Inductively coupled plasma etching of InP using N_2/H_2 ," *Journal of Applied Physics*, vol. 89, pp. 5322-5325, 2001.
102. C. Constantine, C. Barratt, S. J. Pearton, F. Ren, J. R. Lothian, "Smooth, low-bias plasma etching of InP in microwave $Cl_2/CH_4/H_2$ mixtures," *Applied Physics Letters*, vol. 61, pp. 2899-2901, 1992.
103. J. W. Lee, J. Hong, S. J. Pearton, "Etching of InP at $>1\mu m/min$ in Cl_2/Ar plasma chemistries," *Applied Physics Letters*, vol. 68, pp. 847-849, 1996.
104. C.-Z. Sun, J.-B. Zhou, B. Xiong, J. Wang, Y. Luo, "Vertical and smooth, etching of InP by $Cl_2/CH_4/Ar$ inductively coupled plasma at room temperature," *Chinese Physics Letters*, vol. 20, pp. 1312-1314, 2003.
105. B. C. Qui, A. C. Bryce, R. M. D. L. Rue, J. H. Marsh, "Monolithic integration in InGaAs-InGaAsP multiquantum-well structure using laser processing," *IEEE Photonics Technology Letters*, vol. 10, pp. 769-771, 1998.
106. L. Fu, P. Lever, H. H. Tan, C. Jagadish, P. Reece, M. Gal, "Suppression of interdiffusion in InGaAs/GaAs quantum dots using dielectric layer of titanium dioxide," *Applied Physics Letters*, vol. 82, pp. 2613-2615, 2003.
107. Si_3N_4 thermal expansion coefficients, Accuratus Corporation, [Access on: April 5, 2007, Online], <http://www accuratus.com/silinit.html>
108. S. Adachi, *Physical properties of III-V semiconductor compounds InP, InAs, GaAs, GaP, InGaAs and InGaAsP* (John Wiley & Sons, Inc., United States, 1992), Chap. 4.
109. G. L. Li, P. K. L. Liu, "Optical intensity modulators for digital and analog applications," *IEEE Journal of Lightwave Technology*, vol. 21, pp. 2010-2030, 2003.

110. N. K. Dutta, N. A. Olsson, L. A. Koszi, P. Besomi, R. B. Wilson, R. J. Nelson, "Frequency chirp under current modulation in InGaAsP injection lasers," *Journal of Applied Physics*, vol. 56, pp. 2167-2169, 1984.
111. S. O. Kasap, *Optoelectronics and photonics: principles and practices* (Prentice Hall, Inc., United States, 2001) Chap. 7.
112. L. A. Coldren, S. W. Corzine, *Diode lasers and photonic integrated circuits* (John Wiley & Sons, Inc., NY, U.S., 1995), Chap. 6.
113. *BeamPROP™ Version 5.0 Beta* (RSoft Inc, U.S., 2001), Chap. 1.
114. W. P. Huang, C. Xu, S. Chi, S. K. Chaudhuri, "The finite-difference vector beam propagation method: analysis and assessment," *IEEE Journal of Lightwave Technology*, vol. 10, pp. 295-305, 1992.
115. J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, P.-T. Ho, "Higher order filter response in coupled microring resonators," *IEEE Photonics Technology Letters*, vol. 12, pp. 320-322, 2000.
116. W. K. Burns, "Normal mode analysis of waveguide devices, Part I: Theory," *IEEE Journal of Lightwave Technology*, vol. 6, pp. 1051-1057, 1988.
117. L. B. Soldano, E. C. M. Pennings, "Optical multi-mode interference devices based on self-imaging principles and applications," *IEEE Journal of Lightwave Technology*, vol. 13, pp. 615-627, 1995.
118. M. K. Chin, C. Xu, W. P. Huang, "Theoretical approach to a polarization-insensitive single-mode microring resonator", *Optics Express*, vol. 12, pp. 3245-3250, 2004.
119. M. K. Chin, C. W. Lee, and J. Shen, "Polarization-independent vertical coupler for photonics integration", *Optics Express*, vol. 12, pp. 117-123, 2004.
120. R. J. Poton, "Reciprocity in optics," *Reports on Progress in Physics*, vol. 67, pp. 717-754, 2004.

-
121. R. A. Forber, E. Marom, "Symmetric directional coupler switches," *IEEE Journal of Quantum Electronics*, vol. QE-22, pp. 911-919, 1986.
  122. B. Broberg, S. Lindgren, "Refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ layers and InP in the transparent wavelength region," *Journal of Applied Physics*, vol. 55, pp. 3376-3381, 1984.
  123. S. Janz, J.-M. Baribeau, A. Delge, H. Lafontaine, S. Mailhot, R. L. Williams, D.-X. Xu, D. M. Bruce, P. E. Jessop, M. Robillard, "Optical Properties of Pseudomorphic $\text{Si}_{1-x}\text{Ge}_x$ for Si-based waveguides at the $\lambda=1300\text{-nm}$ and 1550-nm telecommunications wavelength bands," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 990-996, 1998.
  124. R. People, "Physics and applications of $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ strained-layer heterostructures," *IEEE Journal of Selected Topics in Quantum Electronic*, vol. QE-22, pp. 1696-1710, 1986.
  125. M. R. T. Pearson, P. E. Jessop, D. M. Bruce, J. Ojha, S. Kovacic, "SiGe-based dual-wavelength demultiplexers and polarization splitters", *Proceeding of SPIE on Silicon-based Optoelectronics*, California, United States, 1999.
  126. M. K. Chin, C.-W. Lee, S. Y. Lee, S. Darmawan, "High Index Contrast Waveguides and Devices," *Applied Optics*, vol. 44, pp. 3077-3086, 2005.
  127. C. J. Magab, A. C. Adams, D. L. Flamm, "Plasma etching of Si and SiO_2 —the effect of oxygen addition to CF_4 plasmas," *Journal of Applied Physics*, vol. 49, pp. 3796-3803, 1978.
  128. J. S. Yu, Y. T. Lee, "Parametric reactive ion etching of InP using Cl_2 and CH_4 gases: effects of H_2 and Ar addition," *Semiconductor Science and Technology*, vol. 17, pp. 230-236, 2002.
  129. G. Taguchi, *Introduction to quality engineering: designing quality into products and processes*, The Asian Productivity Organization, 1986.
-

-
130. I. Adesida, K. Nummila, E. Andideh, J. Hughes, C. Caneau, R. Bhat, R. Holmstrom, "Nanostructure fabrication in InP and related compounds," *Journal of Vacuum Science and Technology B*, vol. 8, pp.1357-1360, 1990.
  131. J. A. Diniz, J. W. Swart, K. B. Jung, J. Hong, S. J. Pearton, "Inductively coupled plasma etching of In-based compound semiconductors in CH₄/H₂/Ar," *Solid-State Electronics*, vol. 42, pp. 1947-1951, 1998.
  132. J. H. Angenent, M. Erman, J. M. Auger, R. Gamonal, P. J. A. Thus, "Extremely low loss InP/GaInAsP rib waveguides," *Electronics Letters*, vol. 25, pp. 628-629, 1989.
  133. J. Zhao, Y.-C. Wang, Z.-C. Feng, I. Ferguson, "Layer combination effect on band gap shift of InGaAsP/InP MQWs by impurity-free vacancy disordering," *Semiconductor Photonics and Technology*, vol. 10, pp. 74-85, 2004.
  134. J. Micallef, E. H. Li, B. L. Weiss, "Effects of interdiffusion on the sub-band-edge structure of In_{0.53}Ga_{0.47}As/InP single quantum wells," *Journal of Applied Physics*, vol. 73, pp. 7524-7532, 1993.
  135. D. Nie, T. Mei, X. H. Tang, M. K. Chin, H. S. Djie, Y. X. Wang, "Argon plasma exposure enhanced intermixing in an undoped InGaAsP/InP quantum-well structure," *Journal of Applied Physics*, vol. 100, 046103, 2006.
  136. C. D. Xu, T. Mei, J. R. Dong, "Determination of diffusion length for intermixed quaternary quantum well with polarized edge-emitting photoluminescence," *Applied Physics Letters*, vol. 90, 191111, 2007.
  137. N. Shimada, Y. Fukumoto, M. Uemukai, T. Suhara, H. Nishihara, S. Larsson, "Selective disordering of InGaAs strained quantum well by rapid thermal annealing with SiO₂ caps of different thicknesses for photonic integration," *Japanese Journal of Applied Physics*, vol. 39, vol. 5914-5915, 2000.
  138. J. S. Yu, J. D. Song, Y. T. Lee, "Dependence of band gap energy shift of In_{0.2}Ga_{0.8}As/GaAs multiple quantum well structures by impurity-free vacancy
-

-
- disordering on stoichiometry of SiO_x and SiN_x capping layers," *Journal of Applied Physics*, vol. 91, pp. 4256-4260, 2002.
139. R. M. Jenkins, R. W. J. Devereux, J. M. Heaton, "Waveguide beam splitters and recombiners based on multimode propagation phenomena," *Optics Letters*, vol. 17, pp. 991-993, 1992.
140. J. M. Heaton, R. M. Jenkins, D. R. Wight, J. T. Parker, J. C. H. Birbeck, K. P. Hilton, "Novel 1-to- N way integrated optical beam splitters using symmetric mode mixing in GaAs/AlGaAs multimode waveguides," *Applied Physics Letters*, vol. 61, pp. 1754-1756, 1992.
141. P. Ambrée, K. Wandel, E. H. Böttcher, D. Bimberg, "Plasma enhanced chemical vapor deposition SiO_2 layers for passivation of InGaAs:Fe metal-semiconductor-metal photodetectors," *Journal of Applied Physics*, vol. 77, pp. 945-947, 1995.
142. Z. L. Yuan, X. M. Ding, B. Lai, X. Y. Hou, E. D. Lu, P. S. Xu, X. Y. Zhang, "Neutralized $(\text{NH}_4)_2\text{S}$ solution passivation of III-V phosphide surfaces," *Applied Physics Letters*, vol. 73, pp. 2977-2979, 1998.
143. O. Mitomi, I. Kotaka, K. Wakita, S. Nojima, K. Kawano, Y. Kawamura, H. Asai, "40-GHz bandwidth InGaAs/InAsAs multiple quantum well optical intensity modulator," *Applied Optics*, vol. 31, pp. 2030-2035, 1992.
144. S. Charbonneau, E. S. Koteles, P. J. Poole, J. J. He, G. C. Aers, J. Haysom, M. Buchanan, Y. Feng, A. Delage, F. Yang, M. Davies R. D. Goldberg, P. G. Piva, I. V. Mitchell, "Photonic integrated circuits fabricated using ion implantation," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 4, pp. 772-793, 1998.
-