Mode Conversions in Active Semiconductor MQW Integrated Optics Devices

Yousef Alahmadi

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MODE CONVERSIONS IN ACTIVE SEMICONDUCTOR MQW INTEGRATED OPTIC DEVICES

by

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ABSTRACT

Optical communication systems had successfully met the increasing demands for higher communication speeds through the utilization of all degrees of freedom of the light propagating in a single mode fiber (SMF). However, the Shannon limit restricts further improvements of the capacity in the SMFs. Space-division multiplexing (SDM) offers a way for further increasing the capacity of optical fibers through the utilization of the spatial domain. However, for it to be successfully implemented, many integral parts of the optical communication must be tuned or modified to work effectively with the multimode fibers, including few mode amplifiers, and mode converters. In this work, we first develop the few mode semiconductor optical amplifier (FMSOA) that provides an equalized-gain for $E_{11}$, $E_{12}$, $E_{21}$, and $E_{22}$ modes. The fabricated InGaAsP MQW FMSOA shows that the modes are confined to the ridge waveguide, overlapping the quantum wells with approximately the same amount, leading to equalized gain for each of the four waveguide modes. Second, we develop an all-optical mode and wavelength converter (AOMWC) using the inter-modal four wave mixing (FWM) process in an FMSOA. At the nonlinear regime of an FMSOA, the interaction of waves with different wavelengths and modes creates gain and index gratings. These gratings provide a very efficient inter-modal FWM process. The high mode selectivity and the efficient FWM make the FMSOA an appealing AOMWC for integrated all-optical signal processors. Lastly, an asymmetric supermode converter is demonstrated by encircling the exceptional point in a non-Hermitian system. Encircling the exceptional point leads to a direction-dependent coalesce of the eigenvalues and merge of the eigenvectors. The supermode converter is designed by manipulating the gain and
the propagation constant along the length of a directional coupler. Independent of the input, the output of the coupler merge to a unique single eigenstate at each end of the coupler.
For my dear parents, and lovely wife
ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. ix

LIST OF TABLES ...................................................................................................................... xvi

LIST OF ACRONYMS ............................................................................................................... xvii

CHAPTER 1: INTRODUCTION .................................................................................................. 1

CHAPTER 2: FOUR-MODE SEMICONDUCTOR OPTICAL AMPLIFIER ................................. 4

  2.1. Introduction ..................................................................................................................... 4

  2.2. Theory and Simulation of Few-Mode Semiconductor Optical Amplifier ................. 6

  2.3. Design of the FM SOA .................................................................................................. 11

  2.4. MQW Structure and Device Fabrication ................................................................. 13

  2.5. Experimental Setup and Device Measurements ...................................................... 18

  2.6. Conclusion ................................................................................................................... 25

CHAPTER 3: MODE CONVERSION IN FMSOA USING FOUR-WAVE MIXING ............. 26

  3.1. Introduction ................................................................................................................... 26

  3.2. Nonlinear Process for All-Optical Signal Processing .............................................. 28

  3.3. Four-Wave Mixing in a Single-Mode SOA ............................................................... 30

  3.4. Four-Wave Mixing in a Few-Mode SOA ................................................................. 32

  3.5. Devices Structure and Fabrication .......................................................................... 38

  3.6. Experiment Setup and Results ............................................................................... 42
3.7. Conclusion........................................................................................................48

CHAPTER 4: MODE CONVERSION IN A SEMICONDUCTOR DIRECTIONAL
COUPLER BY ENCIRCLING THE EXCEPTIONAL POINT ................................49

4.1. Parity-Time Symmetry and Exceptional Point..........................................49

4.2. Design and simulation of the Asymmetric Super-Mode Converter ..........56

4.3. Quantum Well Intermixing of InAlGaAs MQWs.................................68

4.3.1. Introduction...............................................................................................68

4.3.2. Devices Structure and Fabrication............................................................70

4.3.3. Intermixing Characteristics.................................................................74

4.3.4. Lasing Characteristics........................................................................78

4.3.5. Loss Measurements...............................................................................81

4.3.6. Conclusion..............................................................................................83

4.4. Fabrication of the Chiral Supermode Converter.....................................85

4.5. Waveguide’s Gain Characterization.........................................................92

4.6. Experimental Setup and Device Measurements ......................................98

4.7. Conclusion................................................................................................106

LIST OF REFERENCES..........................................................................................107
LIST OF FIGURES

Figure 1-1: Nonlinear capacity curves calculated for a range of transmission distances [2]. ........ 1

Figure 2-1: Modal gain and differential modal gain (DMG) of a 3-mode EDDA [13]. .............. 4

Figure 2-2: Schematic of slab and ridge waveguides ............................................................... 6

Figure 2-3: A plot of the slab waveguide dispersion relation. The effective indexes of the modes are where the plot of the left-hand side (L.H.S) of the equation (red) intercept with the right-hand side of the equation (R.H.S.) of the equation (blue for m=0, Green for m=1, and purple for m=2). .............................................................................................................................................................................................. 8

Figure 2-4: Intensity profile of different modes in a rectangular waveguide ......................... 10

Figure 2-5: Diagram of the index profile, dimensions and simulated mode profiles of the FM SOA........................................................................................................................................................................................................... 12

Figure 2-6: Bandgap diagram and simulated mode profiles of the four-mode SOA demonstrating the strategic placement of the quantum wells to achieve similar overlap integrals for all four modes. .................................................................................................................................................................................................. 12

Figure 2-7: the fabrication process of the InGaAsP MQW FM SOA.................................................. 14

Figure 2-8: a microscopic image of the etched waveguide structure................................. 16

Figure 2-9: (a) Schematic of the experimental setup used to characterize the SOA, and (b) an image of the actual setup................................................................. 18

Figure 2-10: schematic of a vertical phase plate showing the input LP_{01}-like beam and the output LP_{11a}-like beam.............................................................. 19

Figure 2-11: schematic of a horizontal phase plate showing the input LP_{01}-like beam and the output LP_{11b}-like beam.............................................................. 19
Figure 2-12: schematic of a vertical and a horizontal phase plates showing the input LP$_{01}$-like beam and the output LP$_{22}$-like beam................................................................. 20

Figure 2-13: fabricated phase plates ................................................................................................................. 20

Figure 2-14: the output intensity of a circular beam passing through the vertical phase plate..... 21

Figure 2-15: Images of the actual FM SOA mode profiles (a) without bias and (b) with a 40 mA bias. ............................................................................................................................... 22

Figure 2-16: On-off gain as a function of output power without amplification ......................... 23

Figure 2-17: Images of the four modes of our FM SOA with the dimensions of the waveguide superimposed over the image of the E$_{22}$ mode. ........................................................................ 23

Figure 3-1: the generic block diagram of an XOR gate using a nonlinear medium. .......... 29

Figure 3-2: a normalized intensity pattern and the carrier density pattern induced in SM SOA due to the FWM process................................................................. 31

Figure 3-3: Schematic of a simplified FM SOA with a larger cross-section of the active region (brown) compared with that of an SM SOA (white dashed rectangle). Images beside demonstrate the variation of the optical intensity composed of E$_{11}$ and E$_{21}$ mode in the transverse plane of the active region at different positions along the FMSOA. The gain of SOA is neglected for simplicity................................................................................................................................. 33

Figure 3-4: Illustrations of mode selective parallelogram rule in frequency-mode number planes. Any wave is represented by a point in the frequency-mode number plane. Any waves at the four vertices of a parallelogram effectively interact with each other. Base on the shape of a parallelogram, the waves interactions are classified as: (a) few-mode degenerate FWM, (b) few-mode partial degenerate FWM and (c) few-mode non-degenerate FWM. Single-mode FWM such
as: (d) degenerate FWM and (e) non-degenerate FWM are special cases of the few-mode FWMs. Generalized mode number to negative can account for counter-propagation FMW such as: (f) few-mode counter-propagation FWM and (g) single-mode counter-propagation FWM.

Figure 3-5: Schematics of the InAlGaAs MQW bandgap diagram grown using MOCVD.

Figure 3-6: Schematic of the InAlGaAs MQW FM SOA with n-contact propping the full ridge-waveguides.

Figure 3-7: Schematic of the InAlGaAs MQW FM SOA with n-contact propping half the ridge-waveguides while the BCB layer is isolating the other half of the waveguides. The n-contact is removed from the schematic of one FM SOA to show the covered features.

Figure 3-8: Schematic of the experiment setup used to characterize FWM in the FM SOA.

Figure 3-9: Output of the FM SOA, where the dotted circles represent the part of modes overlapping the SMF.

Figure 3-10: The output spectra of the InAlGaAs MQW FM SOA when two fundamental-mode waves were lunched into the FM SOA at bias currents of 90 mA.

Figure 3-11: The output spectra of the InAlGaAs MQW FM SOA when two fundamental-mode waves were lunched into the FM SOA at bias currents of 115 mA.

Figure 3-12: Illustration of exited and detected waves for the FM SOA mode conversion experiment.

Figure 3-13: intensity of the output pumps, probe and converted signal as function of injected pumps.

Figure 3-14: intensity of converted signal as a function of pump and probe frequency detuning.

Figure 4-1: Schematic of a standard waveguide coupler.
Figure 4-2: Schematic of a PT-Symmetric waveguide coupler.......................................................... 53

Figure 4-3: Schematic of the waveguide coupler designed to provide an EP encirclement........ 56

Figure 4-4: The EP in the real and imaginary plane of the relative propagation constants and the
CW and CCW loops around the EP demonstrated by the waveguide coupler. ......................... 57

Figure 4-5: The differential propagation constant and the gain used for the simulation of the
waveguide coupler. ....................................................................................................................... 58

Figure 4-6: The simulated evolution of the waves with a random initial state in the waveguide
coupler. The upper graphs show the a) intensity and b) phase evolutions during CW encirclement
around the EP, and the lower graphs show the c) intensity and d) phase evolutions during CCW
encirclement..................................................................................................................................... 59

Figure 4-7: The simulated evolution of the several waves with varying initial state in the
waveguide coupler. The upper graphs show the a) intensity and b) phase evolution during CW
encirclement around the EP, and the lower graphs show the c) intensity and d) phase evolution
during CCW encirclement.................................................................................................................. 60

Figure 4-8: The simulated CCW loop around the EP with the color map showing the relative
phase acquired as the waves propagate in the coupler..................................................................... 61

Figure 4-9: The simulation of a couple of a) CCW loop and b) CW loop that do not enclose the
EP.................................................................................................................................................. 62

Figure 4-10: A cross-sectional schematic of the waveguide coupler. ............................................. 63

Figure 4-11: The simulated mode profile of a 4μm-wide InAlGaAs MQW waveguide with a
ridge depth of 1.07 μm. .................................................................................................................... 64

Figure 4-12: The simulated coupling of two 4μm-wide InAlGaAs MQW waveguides spaced by
3μm and have a ridge depth of 1.07 μm. .......................................................................................... 64

xii
Figure 4-13: The effective index of the InAlGaAs MQW waveguide as a function of the width. 65
Figure 4-14: The relative propagation constants normalized to the coupling coefficient as a function of width. ................................................................. 66
Figure 4-15: Band diagram of a quantum well/barriers of InAlGaAs QW and InGaAsP QW. ... 68
Figure 4-16: The quantum well intermixing process. ................................................................. 69
Figure 4-17: Schematics of the InAlGaAs MQW bandgap diagram grown using MOCVD. ..... 71
Figure 4-18: Schematic of the InAlGaAs MQW laser diodes. .................................................. 73
Figure 4-19: The wavelength shifts (and the lasing spectra) of the as-grown, intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers. .................................................. 73
Figure 4-20: The L-I curve of the as-grown, intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers ................................................................. 79
Figure 4-21: Threshold current of the intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers. .................................................................................. 80
Figure 4-22: Slope efficiency of the intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers. .................................................................................. 80
Figure 4-23: Schematic of the setup used to observe the Fabry-Perot fringes of the intermixed InAlGaAs MQW laser cavities. ................................................................. 82
Figure 4-24: (a) Detected Fabry-Perot fringes by wavelength scanning of the light launching a single intermixed InAlGaAs MQW laser, and (b) Loss coefficients of the intermixed InAlGaAs MQW laser found at 1590 nm ................................................................. 83
Figure 4-25: The fabrication the alignment marks. ................................................................. 85
Figure 4-26: The QWI process of the InAlGaAs MQW ................................................................ 86
Figure 4-27: A microscopic image of the intermixing-promoted film on the sample .......... 87
Figure 4-28: Images of the patterned SiN_x features................................................................. 88
Figure 4-29: The fabrication process of the waveguide structure............................................. 89
Figure 4-30: The application of the BCB and the metal contact. ................................................ 90
Figure 4-31: A schematic of the fabricated InAlGaAs MQW waveguide coupler with the top metal contact exposed from the far-right coupler and waveguide to show the underlying features. ................................................................................................................................. 91
Figure 4-32: The experimental setup for characterizing the gain profile of a single waveguide. 92
Figure 4-33: the normalized detected intensity as a function of the position of the probe. The z=0 point of the z-axis is located at the output facet of the waveguide. ................................................. 93
Figure 4-34: the estimated gain profile that provides a reasonable fit of measured output power. ................................................................................................................................................. 95
Figure 4-35: The estimated gain profile of four probes spaced evenly, each one is biased with a peak gain of 46cm^{-1}. The average gain is less than 0.................................................... 96
Figure 4-36: The estimated gain profile of four probes spaced evenly, each one is biased with a peak gain of 48cm^{-1}. The average gain is more than 0. .................................................... 96
Figure 4-37: the normalized lasing spectrum of a single 1.5 cm long InAlGaAs MQW waveguide biased by four 550mA probes............................................................... 97
Figure 4-38: the gaussian-like gain profile induced to the coupled waveguides using 4 probes. 98
Figure 4-39: Simulation of the far-field of the |1⟩ and |2⟩ supermodes of the waveguide coupler. ................................................................................................................................. 99
Figure 4-40: Captured far-field images of the coupled waveguide when the propagating wave experiences a CCW encirclement around the EP. ......................................................... 100
Figure 4-41: Captured far-field images of the coupled waveguide when the propagating wave experiences a CCW encirclement around the EP. The gain of the IR camera was amplified in the right images. 101

Figure 4-42: A gaussian-like gain profile induced to the coupled waveguides a peak gain smaller the coupling coefficient. 102

Figure 4-43: The far-field images of a waveguide coupler without the width modulation of the passive waveguide, a waveguide coupler with modulated width but low peak gain, and the same waveguide coupler but with high peak gain. 104

Figure 4-44: Captured far-field images of the coupled waveguide when the propagating wave experiences a CW encirclement around the EP. 105
LIST OF TABLES

Table 2-1: Epitaxial layer structure of FM-SOA .................................................................................................................. 14
Table 2-2: PECVD recipe for growing SiO₂ .......................................................................................................................... 15
Table 2-3: Contact-mask photolithography for S1805 ........................................................................................................... 15
Table 2-4: RIE recipe for etching SiO₂ ................................................................................................................................. 16
Table 2-5: Wet etching recipes for InGaAs and InP layers .................................................................................................... 16
Table 2-6: Contact-mask photolithography for NR7-3000PY ............................................................................................... 17
Table 3-1: Epitaxial layer structure of the InAlGaAs MQW wafer ...................................................................................... 39
Table 4-1: Point defects and resulted in QW diffusion when several MQW structures are capped with SiO₂ and SiNx during the RTA.......................................................................................................................... 77
### LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOMWC</td>
<td>All-Optical Mode And Wavelength Converter</td>
</tr>
<tr>
<td>AOSP</td>
<td>All-Optical Signal Processing</td>
</tr>
<tr>
<td>AOWC</td>
<td>All-Optical Wavelength Converter</td>
</tr>
<tr>
<td>BOE</td>
<td>Buffered Oxide Etch</td>
</tr>
<tr>
<td>CCW</td>
<td>Counter-Clockwise</td>
</tr>
<tr>
<td>CDP</td>
<td>Carrier Density Pulsation</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>CW</td>
<td>Clockwise</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized</td>
</tr>
<tr>
<td>DMG</td>
<td>Differential Modal Gain</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>EO</td>
<td>Electrical-To-Optical</td>
</tr>
<tr>
<td>EP</td>
<td>Exaptational Point</td>
</tr>
<tr>
<td>EP</td>
<td>Exceptional Point</td>
</tr>
<tr>
<td>FM</td>
<td>Few-Mode</td>
</tr>
<tr>
<td>FMF</td>
<td>Few-Mode Fiber</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width At Half Maximum</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropyl Alcohol</td>
</tr>
<tr>
<td>MQW</td>
<td>Multiple Quantum Well</td>
</tr>
<tr>
<td>MSPR</td>
<td>The Mode-Selective Parallelogram Rule</td>
</tr>
<tr>
<td>OE</td>
<td>Optical-To-Electrical</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonic Integrated Circuits</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonic Integrated Circuits</td>
</tr>
<tr>
<td>SDM</td>
<td>Space-Division Multiplexing</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SM</td>
<td>Single Mode</td>
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<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
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CHAPTER 1: INTRODUCTION

In a work published in 1948 [1], Claude Shannon studied the capacity of an additive white Gaussian noise channel and, by doing so, introduced the “information theory” [2, 3]. The capacity is defined as the maximumly achievable transmission rate with a specified error-rate. According to his work, the capacity of a noise-limited channel increases linearly with the increase of power. For the decades following Shannon’s work, information theory has been extended to many complex channels, including fiber channels. In single-mode wavelength-division multiplexed (WDM) fiber channels, increasing the power increases the cross-talk between different channels due to the fiber’s Kerr nonlinearity. Since different WDM channels are routed to different locations, the nonlinear distortion of a WDM channel cannot be compensated for by the receiver, effectively acting as unpredictable noise at high signal power. Therefore, even though the signal-to-noise ratio (SNR) improves with the increase of the power of the signal, the nonlinear effective-noise form spectrally-adjacent channels limits the capacity of fiber as shown in figure 1-1 [2].

![Figure 1-1: Nonlinear capacity curves calculated for a range of transmission distances [2].](image-url)
Several technological breakthroughs, such as erbium doped fiber amplifier (EDFA), wavelength division multiplexing and coherent detection, have increased the fiber’s capacity by an order of magnitude every four years through the utilization of amplitude, phase, frequency, and polarization of the light propagating in a single modes fiber (SMF) [3], [4]. However, the current SMF capacity is very close to the Shannon limit [3]–[6]. Thus, further improvements of the transmission rate require exploration of a new domain of the optical communication system.

Space-division multiplexing (SDM) offers a way for further increasing the capacity of optical fibers through the utilization of the spatial domain of the light. Within a single fiber, SDM utilizes multiple spatial channels for data transmission through the use of different core regions in multicore fibers, or the use of different propagating modes in multimode fibers and few-mode fibers. Assuming the noise of each spatial channel is identical to the noise of an SMF channel, the capacity of the SDM fiber with M spatial channels is M times the capacity of the SMF. A transmission capacity beyond the Shannon limit of SMF and reduced power consumption, compared a bundle of SMFs, have been demonstrated using SDM [3]–[7]. However, reduced implantation cost compared to a bundle of SMF and efficient signal processing components are crucial for the SDM to be commercially implemented.

In the first chapter of this dissertation, we demonstrate the first few-mode (FM) semiconductor optical amplifier (SOA) designed for the E_{11}, E_{12}, E_{21}, and E_{22} modes using InGaAsP MQW [8]. The FM SOA provide a gain-equalized amplification for the aforementioned modes with high integrability for photonic integrated circuits (PICs) and low cost. In chapter two, a novel all-optical mode and wavelength converter (AOMWC) is developed using the inter-modal four-wave mixing (FWM) properties of an FM SOA fabricated using InAlGaAs MQW [9], [10].
The highly efficient inter-modal FWM demonstrated in this work shows a great potential of the FM SOA for all-optical signal processing (AOSP). In chapter three, we demonstrate an active super-mode converter by encircling an exaptational point (EP) in a semiconductor directional coupler. The asymmetric, current-controlled converter consists of a coupled InAlGaAs MQW optical waveguides with varying real and imaginary parts of the propagation constants along the propagation direction to provide a unique encirclement direction for the light propagating along each of counter-propagating directions. As a result, a unique super-mode is generated for each propagation direction of the semiconductor coupler.
CHAPTER 2:  FOUR-MODE SEMICONDUCTOR OPTICAL AMPLIFIER

2.1. Introduction

Few-mode (FM) amplification using erbium-doped fiber amplifier (EDFA) is achievable by replacing the single-mode fibers (SMFs) in the configuration of the EDFA with few-mode fibers (FMFs) [7], [11], [12]. However, since the loss/gain coefficient is mode dependent, As shown in figure 2-1, the DMG of a 3-mode EDFA, as an example, can reach 6dB over the C-band (1530nm – 1565nm) [13]. The high DMG, which is wavelength dependent, limits the FM EDFA’s compatibility with already established efficient technologies, such as WDM. Thus, creative and cost-efficient configurations of optical amplification had to be developed to provide a gain-equalized gain over a broad bandwidth.

![Modal gain and differential modal gain (DMG) of a 3-mode EDDA](image)

Figure 2-1: Modal gain and differential modal gain (DMG) of a 3-mode EDDA [13].

To achieve a gain-equalized amplification in an FM EDFA, two approaches were pursued. In the first approach, the modal gain can be equalized through tailoring of the pump profile of the FM EDFA. For example, for a 3-mode EDFA, gain equalization can be achieved using the LP₁₁ mode as the forward pump, and pumping the LP₀₂ mode in the backward direction.
While it is indeed capable of delivering the desired equalized gain, it contains approximately the same amount of components that three independent single-mode EDFAs would. Therefore, there would not be much cost savings over a parallel-WDM system utilizing independent SM EDFAs. Furthermore, interdependencies between modes make FM EDFA performance subpar to SM EDFAs.

In the second approach, the gain of the FM EDFA can be equalized through tailoring of the Erbium dopant in the EDFA. Ring-shaped Erbium doping has been adopted in the design of a 4-mode FM-EDFA with a uniform pump profile to reduce the DMG [14]. Even though an-almost-zero DNG was predicted using the theoretical model, the experimental result showed much higher DMG. The geometry of the Erbium doping was prepared using Modified Chemical Vapor Deposition combined to solution-doping. It can be hard to achieve a well-defined Erbium doping geometry using this method. Several works [13] have investigated a combination of the tailoring of the Erbium dopant with the tailoring of the pump profile, adopted more complex Erbium doping geometry, and/or adopted different techniques for fabricating the Erbium doping profile of the FM EDFA.

The difficulty in engineering a gain-equalized EDFA for SDM motivate research into FM semiconductor optical amplifiers (SOA). FM SOAs have the potential to provide gain-equalized amplification for multiple input modes without the additional component complexity of the aforementioned multi-mode EDFA setups, making them more economically appealing [8].
2.2. Theory and Simulation of Few-Mode Semiconductor Optical Amplifier

SOA usually utilizes a rectangle waveguide structure, such as rib waveguide or ridge waveguide, to provide a 2-dimensional confinement for propagating lights. To understand the confinement behavior of a rectangle waveguide, we can consider a dielectric planer (slab) waveguide first (fig. 2-2). The structure of the slab waveguide consists of three layers: substrate, core, and cladding. The slab waveguide confines the light in the vertical direction using total internal reflection at the interfaces between the core and the cladding/substrate. As the wave reflects from one interface, propagates to the second interface and reflects, the wave will self-interfere. Only waves that constructively self-interfere will propagate in the slab waveguide. Each one of the constructively interfering waves is represented with a transverse mode number \( m \) and have a propagation constant \( \beta_m \). Since the slab waveguide has a uniform refractive index \( n \) and field \( E \) in the horizontal direction \( \frac{\partial^2}{\partial y^2} = 0 \), the wave equation for each region (cladding \( c \), core \( g \), and substrate \( s \)) can be written as:

\[
\frac{\partial^2}{\partial y^2} = 0
\]

Figure 2-2: Schematic of slab and ridge waveguides
\[
\frac{\partial^2}{\partial x^2} E(x,y) + [k_0^2 n_i^2 - \beta^2] E(x,y) = 0 \tag{2-1}
\]

where \(k_0\) is the free-space propagation constant, \(n\) is the refractive index of region \(i\), \(i = c\) for the cladding region, \(i = g\) for the core region, and \(i = s\) for the substrate region. Please note that each mode is a solution of the wave equations in the three regions, and each mode propagate with the same propagation constant \((\beta_m)\) in all three regions. By examining the wave equation (2-1), we can see that in each region, the solution \((E(x,y))\) can be an exponential function if \(\frac{1}{E(x,y)} \frac{\partial^2}{\partial x^2} E(x,y) > 0\), or a sinusoidal function if \(\frac{1}{E(x,y)} \frac{\partial^2}{\partial x^2} E(x,y) < 0\). Furthermore, at the interfaces between the regions, the solution \((E(x,y))\) has to contentious. By satisfying the boundary condition at the interfaces between the regions and looking for a guided solution, we can see that a guided solution is only possible if \(E(x,y)\) is sina usoidal function in the core region and \(E(x,y)\) is exponential in cladding and substrate regions. This requires that \(k_0 n_c > \beta_m, \beta_m > k_0 n_s,\) and \(\beta_m > k_0 n_c\).

The number of transverse modes propagating in a slab waveguide depends on the height of the core region and the refractive index difference between the core and cladding\(\backslash\)substrate layers. The following dispersion relation in a slab waveguide can be derived using the wave equations (2-1) and the boundary conditions:

\[
k_0 t_g \sqrt{n_g^2 - n_{mode}^2} = \tan^{-1} \left( \alpha_c \sqrt{n_{mode}^2 - n_c^2} \right) + \tan^{-1} \left( \alpha_s \sqrt{n_{mode}^2 - n_s^2} \right) + m\pi \tag{2-2}
\]

where \(t_g\) is the thickness of the core region, \(n_{mode}\) is the effective refractive index of the mode and it relates to mode’s propagation constant by \(\beta_m = k_0 n_{mode}\). For the TE modes, \(\alpha_c = \alpha_s = 1\). For the TM modes, \(\alpha_c = \frac{n_g^2}{n_c^2}\) and \(\alpha_s = \frac{n_g^2}{n_c^2}\). The dispersion relation (2-2) can be solved for
$n_{\text{mode}}$ graphically. For example, a symmetric slab waveguide is assumed with $n_c = n_s = 3.32$, $n_g = 3.4$, $t_g = 3.1 \, \mu m$, and $\lambda = 1.55 \, \mu m$. The left-hand side (L.H.S) and the right-hand side (R.H.S.) of the equation is plotted for each value of $m$ in figure (2-3). Figure (2-3) shows that the waveguide can support three slab modes with $n_0 = 3.393$, $n_1 = 3.374$, $n_2 = 3.344$.

![Graph of slab waveguide dispersion relation](image)

**Figure 2-3:** A plot of the slab waveguide dispersion relation. The effective indexes of the modes are where the plot of the left-hand side (L.H.S) of the equation (red) intercept with the right-hand side of the equation (R.H.S.) of the equation (blue for $m=0$, Green for $m=1$, and purple for $m=2$).

The cut-off condition for $t_g$ to guide the $m^{th}$ mode can also be derived from the dispersion relation (2-2) by setting $n_{\text{mode}} = n_s$ (assuming $n_s < n_c$), which yield:

$$t_m = \frac{\tan^{-1}\left(\frac{\alpha s}{k \sqrt{n_g^2-n_s^2}}\right)+m\pi}{k o \sqrt{n_g^2-n_s^2}} \quad (2-3)$$
On the other hand, a ridge waveguide (fig. 2-2) provide a 2D confinement of the propagating light. Similar to a slab waveguide, the ridge waveguide confine the light through total internal reflection. In the vertical direction, the total internal reflection happens at the interfaces between the films. In the horizontal direction, the effective refractive index in the area covered with a cladding layer is different from the effective index in the areas with striped cladding. This disparity of the effective refractive indexes causes total internal reflections and make a weakly-guided waveguide in the horizontal direction. Marcatili's method can be used to analytically solve for propagating modes using the same equations derived for the slab waveguide. Marcatili's method divides the waveguide to three vertical sections, one containing the substrate, core, and cladding of the waveguide (section II); and the two adjacent sections (sections I, and III) (fig. 2-2). The dispersion relation of the slab waveguide can be used to find the effective mode index for each section ($n_I$, $n_{II}$, and $n_{III}$). Next, by rotating our point of few around the z-direction and substituting the effective indexes into the dispersion relation again, the horizontal confinement of the modes can be solved. Note that by rotating the point of few, the polarization of the light will be switched (TE to TM or TM to TE). Thus, $\alpha_c$ and $\alpha_s$ have to be adjusted accordingly. Furthermore, each mode is now represented by two numbers; $m_h$: representing the mode number in the horizontal direction and $m_v$: representing the mode number in the vertical direction. Each mode has a unique intensity profile and is labeled by $E_{l,p}$ in a rectangular waveguide, where $l$ is the number of intensity peaks in the vertical direction ($l = m_v + 1$) and $p$ is the number of intensity peaks in the horizontal direction ($p = m_h + 1$) (fig. 2-4). One important property of the optical mode is the overlap integral ($\Gamma$). Overlap integral is defined as the ratio of the energy in a mode that is carried in the core of the waveguide over the total energy of the mode:
\[ \Gamma = \frac{\int_{-y}^{0} |E|^2 \, dx}{\int_{-\infty}^{\infty} |E|^2 \, dx} \] (2-4)

Figure 2-4: Intensity profile of different modes in a rectangular waveguide
2.3. Design of the FM SOA

InGaAsP multiple quantum well (MQW) is used in our design for the FM SOA since it operates at a wavelength of 1550 nm, used for most optical communication systems. The InGaAsP MQWs are usually embedded in an InGaAsP light guiding layer with a refractive index $n_g = 3.3877$. Meanwhile, both substrate and cladding layers consist of InP with a refractive index $n_s = n_c = 3.1659$ [15]. Since the refractive indexes of the top cladding and the substrate are equal, the waveguide is symmetric and will always support the fundamental mode ($E_{11}$).

Using equation (2-3), the cut-off thickness of a core layer that supports the $E_{12}$ and $E_{13}$ modes were found to be $tg(E_{12}) = 0.64 \, \mu m$ and $tg(E_{13}) = 1.28 \, \mu m$. Our goal in this project is to design a FM SOA that provide an equalized gain for $E_{11}, E_{12}, E_{21}$, and $E_{22}$.

A core thickness of 1 $\mu$m, waveguide width of 5 $\mu$m, and the cladding thickness of 1.6 $\mu$m were used for our design of the FMSOA. FemSIM software of RSoft was utilized to simulate the supported modes of the suggested waveguide structure. Figure 2-5 illustrates the simulated mode profiles of the FM SOA, including the indices of refraction and the dimensions of the waveguide. The calculated overlap integrals for the $E_{11}$ and $E_{21}$ modes, which have only one lobe in the vertical direction, are 12.9% and 16.7%, respectively. Similarly, the $E_{12}$ and $E_{22}$ modes have overlap integrals calculated to be 16.9% and 17.5%, respectively. Figure 2 illustrates the images of the waveguide modes superimposed onto the waveguide structure, and includes the position of the quantum wells, providing a very clear illustration of the strategic placement of the quantum wells such that all four modes have similar overlap integrals. Due to the geometric asymmetry of the waveguide, the $\frac{1}{e^2}$ full width of the $E_{11}$ mode is 5.2 $\mu$m in the x-direction and 1 $\mu$m in the y-direction. This mode aspect ratio does not match that of the $LP_{01}$ mode in FMFs,
leading to reduced coupling efficiency. Similar mismatches apply to high-order modes. This issue can be addressed by using the combination of an objective lens and a cylindrical lens.

Figure 2-5: Diagram of the index profile, dimensions and simulated mode profiles of the FM SOA.

Figure 2-6: Bandgap diagram and simulated mode profiles of the four-mode SOA demonstrating the strategic placement of the quantum wells to achieve similar overlap integrals for all four modes.
2.4. **MQW Structure and Device Fabrication**

Our four-mode SOA has the familiar structure of a P-I-N diode. As shown in table 2-1, the top layer is P-doped, the middle layer is intrinsic, and the bottom layer and substrate are N-doped. In this configuration, the waveguide has an index of refraction of 3.3877 and thickness of 1 μm, the substrate and cladding have indices of 3.1659, and above the cladding is air. The cladding thickness is 1.6 μm.

The P and N-type layers have the same bandgap of 1.344 eV, while the intrinsic layer, where amplification occurs, is very rich and has a symmetric structure that contains seven strategically placed quantum wells. 200 nm down from the top layer resides the first group of three quantum wells with a thickness of 6 nm each, which have a bandgap of 0.77 eV, corresponding to a wavelength of 1.61 μm. The quantum wells in this group are separated by two 10 nm thick barrier layers, which have a bandgap of 0.954 eV, corresponding to a wavelength of approximately 1.3 μm. 350 nm further down from the first group of quantum wells resides a single quantum well of the same thickness and bandgap as those of the quantum wells found in the groups. Following this is the constructed group of another three quantum wells. Figure 2-6 contains the bandgap diagram of our FM SOA.

The P-I-N diode is forward biased, causing the Fermi levels to split and allowing electrons and holes to occupy the quantum wells simultaneously. The quantum well regions are where the optical gain occurs, and therefore it is important that these be placed such that the overlap integrals between the waveguide modes and the quantum well regions are similar for all four modes.
Table 2-1: Epitaxial layer structure of FM-SOA

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Doping (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-Contact</td>
<td>InGaAs</td>
<td>100</td>
<td>P = 1.3×10¹⁹</td>
</tr>
<tr>
<td>Top cladding</td>
<td>InP</td>
<td>1300</td>
<td>P = 1.0×10¹⁸</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>200</td>
<td>P = 5.0×10¹⁷</td>
</tr>
<tr>
<td>Etch Control</td>
<td>InGaAsP (1.3Q)</td>
<td>50</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>50</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>InGaAsP (1.3Q)</td>
<td>106</td>
<td>Undoped</td>
</tr>
<tr>
<td>3-QW/barrier</td>
<td>InGaAsP (1.61Q)/(1.3Q)</td>
<td>6×3/10×2</td>
<td>Undoped</td>
</tr>
<tr>
<td>1-QW</td>
<td>InGaAsP (1.3Q)</td>
<td>353</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>InGaAsP (1.61Q)</td>
<td>6</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>InGaAsP (1.3Q)</td>
<td>353</td>
<td>Undoped</td>
</tr>
<tr>
<td>3-QW/barrier</td>
<td>InGaAsP (1.61Q)/(1.3Q)</td>
<td>6×3/10×2</td>
<td>Undoped</td>
</tr>
<tr>
<td>Lower Cladding</td>
<td>InGaAsP (1.3Q)</td>
<td>106</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>200</td>
<td>N = 5.0×10¹⁷</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>1300</td>
<td>N = 1.0×10¹⁸</td>
</tr>
<tr>
<td>Substrate</td>
<td>InP</td>
<td></td>
<td>N = 5.2×10¹⁸</td>
</tr>
</tbody>
</table>

Figure 2-7: the fabrication process of the InGaAsP MQW FM SOA.
The fabrication process (fig. 2-7) of the FM SOA begins by cleaning a multi-quantum-well wafer sample in an ultrasonic acetone bath to remove debris and organic residue from the surfaces. The sample then is rinsed by isopropyl alcohol (IPA) and deionized (DI) water and placed in a buffered oxide etch (BOE) to remove any native oxide grown during storage. The ridge waveguide is then defined by first depositing a layer of SiO$_2$ film on top of the entire wafer using plasma-enhanced chemical vapor deposition (PECVD) (table 2-2) and then delineating a 5 μm wide SiO$_2$ strip using contact-mask lithography (table 2-3) and reactive-ion etching (table 2-4). The photoresist stripes were then removed using Acetone bath, and the ridge waveguide is created by wet etching, using the SiO$_2$ layer as a mask, down to the etch-stop layer – the very top of the intrinsic region (table 2-5). A microscopic image of the etched waveguides are shown in figure 2-8.

Table 2-2: PECVD recipe for growing SiO$_2$

<table>
<thead>
<tr>
<th>Pressure (mTorr)</th>
<th>1050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>250</td>
</tr>
<tr>
<td>RF Power</td>
<td>25</td>
</tr>
<tr>
<td>SiH$_4$ (sccm)</td>
<td>200</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>412</td>
</tr>
<tr>
<td>Rate (nm/min)</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 2-3: Contact-mask photolithography for S1805

<table>
<thead>
<tr>
<th>Spin (S1805)</th>
<th>3500 rpm for 40 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft-Bake</td>
<td>120 °C for 4 min</td>
</tr>
<tr>
<td>UV Exposure</td>
<td>10 mW/cm$^2$ for 7.2 s</td>
</tr>
<tr>
<td>Develop</td>
<td>351/DI water (1:7) for 20 s</td>
</tr>
<tr>
<td>Hard-Bake</td>
<td>120 °C for 4 min</td>
</tr>
</tbody>
</table>
**Table 2-4: RIE recipe for etching SiO₂**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (mTorr)</td>
<td>75</td>
</tr>
<tr>
<td>RF Power</td>
<td>175</td>
</tr>
<tr>
<td>O₂</td>
<td>5</td>
</tr>
<tr>
<td>CF₄</td>
<td>45</td>
</tr>
<tr>
<td>Rate (nm/min)</td>
<td>56</td>
</tr>
</tbody>
</table>

**Table 2-5: Wet etching recipes for InGaAs and InP layers**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Etching solution</th>
<th>Etch rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs</td>
<td>H₃PO₄:H₂O₂:H₂O (3:1:25)</td>
<td>150 nm/min</td>
</tr>
<tr>
<td>InP</td>
<td>HCl:H₃PO₄ (1:1)</td>
<td>1 μm/min</td>
</tr>
</tbody>
</table>

**Figure 2-8: a microscopic image of the etched waveguide structure**

Once the waveguide has been formed, the top contact is formed by first spin coating the chip with Benzocyclobutene (BCB) at 3500 rpm for 40s, which is fully cured in a nitrogen-only...
environment at 250 °C for 2 hours. The BCB film is thinned by O₂ reactive-ion etching until the very top of the waveguide is exposed. As each chip is created to have multiple waveguide structures to be used independently, NR7-3000PY photoresist is used to define and isolate the top contacts using contact-mask photolithography and later lift-off process (table 2-7). The top electrode is created by depositing 8 nm of titanium, 20 nm of zinc, and 300 nm of gold using vacuum thermal air evaporation. After thinning the sample down to approximately 200 μm and polishing it, the bottom contact is created by depositing 5 nm of nickel, 20 nm germanium, and 180 nm gold using thermal evaporation.

Table 2-6: Contact-mask photolithography for NR7-3000PY

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin (NR7-3000PY)</td>
<td>4000 rpm for 40 s</td>
</tr>
<tr>
<td>Soft-Bake</td>
<td>100 °C for 1 min</td>
</tr>
<tr>
<td>UV Exposure</td>
<td>10 mW/cm² for 19 s</td>
</tr>
<tr>
<td>Hard-Bake</td>
<td>150 °C for 1 min</td>
</tr>
<tr>
<td>Develop</td>
<td>RD6 for 15 s</td>
</tr>
</tbody>
</table>
2.5. Experimental Setup and Device Measurements

Figures 2-9(a) and 2-9(b) are a schematic and an image of the setup used to characterize the FM SOA. This setup is used to excite and image each waveguide mode individually. A polarization controller is used to ensure that only TE modes are excited, as the current SOA only exhibits waveguide gain for the TE polarization. The lens pair, consisting of a 10× and 60× lens, is used to transform the beam spot size from an SMF launch fiber to match the mode size of the SOA. We did not use the combination of an objective lens and a cylindrical lens because of its complexity.

Figure 2-9: (a) Schematic of the experimental setup used to characterize the SOA, and (b) an image of the actual setup.

In order to convert the single-mode output of the SMF to higher order modes, phase plates were fabricated and used (fig 2-10, 2-11, 2-12). The phase plate has two sides with slightly different thickness for each side. The different in thickness between the two sides ($\Delta l$) is carefully adjusted in order for a wave propagation in one side to acquire a $\Delta \phi = \pi$ phase shift compared to the same wave propagating in the other side. Therefore, when a circular LP$_{01}$-like beam is directed to the center of the phase plate, it gets converted to an LP$_{11}$-like beam (fig 2-9, 2-10). The phase plate is fabricated by growing SiO$_2$ on a circular glass plate using the PECVD. The refractive index of the PECVD-grown SiO$_2$ was measured using ellipsometer. Accordingly,
the thickness difference was set to $\Delta l = \frac{\lambda}{2(n_{SiO_2} - n_{air})} = 1.74 \mu m$. A 3.5 $\mu m$-thick film was grown on the glass plate, and a 130 nm-thick Cr was deposited on the SiO$_2$ film using the thermal evaporator. Photolithography was used to cover half of the plate with positive photoresist, and Cr etchant was used to wet etch the uncovered side of the Cr. The photoresist is then removed using acetone bath, and the exposed part of the SiO$_2$ was dry etched using Cr film as a mask. After etching the SiO$_2$, the Cr mask was removed using Cr etchant. The final phase plates are shown in figure 2-13. Figure 2-14 shows the intensity profile captured using IR camera of an LP$_{01}$-like beam passing through the vertical phase plate.

Figure 2-10: schematic of a vertical phase plate showing the input LP$_{01}$-like beam and the output LP$_{11a}$-like beam.

Figure 2-11: schematic of a horizontal phase plate showing the input LP$_{01}$-like beam and the output LP$_{11b}$-like beam.
Figure 2-12: schematic of a vertical and a horizontal phase plates showing the input LP₀₁-like beam and the output LP₂₂-like beam.

Figure 2-13: fabricated phase plates
To generate each of the modes, two phase plates are employed. If no phase plates are used, the $E_{11}$ mode is excited. If only the horizontal phase plate is used, then the $E_{12}$ mode is excited (fig. 2-10). Likewise, if only the vertical phase plate is used, then the $E_{21}$ mode is excited (fig. 2-11). Finally, if both phase plates are used, the $E_{22}$ mode is excited (fig. 2-12). Forward biasing of the FM SOA is accomplished by means of a probe, and a 40× microscope objective is used to magnify the output facet in order to image the mode profiles with a camera. The entire SOA is only 1.33 mm long. An aperture is used to spatially filter out most of the amplified spontaneous emission (ASE).

Images of the mode profiles with and without biasing can then be collected. Figure 2-15 shows images of the mode profiles without any bias, and with a 40 mA bias. Clearly, all of the modes are intensified when the diode is biased, effectively confirming that the SOA does indeed induce optical gain.
Figure 2-15: Images of the actual FM SOA mode profiles (a) without bias and (b) with a 40 mA bias.

Figure 2-9 is a plot of the on-off gain as a function of output power without amplification. As evident in Figure 2-16, the on-off gain is equalized for all four waveguide modes. However, the gain is significantly saturated to around 2 dB at high input power levels. This saturation also manifests in the amplified spontaneous emission (ASE) produced in the waveguide region. A comparison of the ASE output power versus bias current between our SOA and a commercially available chip of similar dimensions shows an approximately 25 dB lower ASE power for our device.

The reason for the low level of output power/amplification is because our current SOA has significant amounts of electronic and optical leakage. Figure 2-17 shows the four amplified SOA mode profiles without the aforementioned spatial aperture. As can be seen in Figure 2-15, in addition to the desired ridge waveguide modes, the chip supports slab waveguide modes that can be excited from amplified spontaneous emission. High-order guided modes are easier to be coupled into the first-order slab mode because of weaker confinement in the horizontal direction.
Figure 2-16: On-off gain as a function of output power without amplification

Figure 2-17: Images of the four modes of our FM SOA with the dimensions of the waveguide superimposed over the image of the $E_{22}$ mode.
To investigate the effect of the mismatch of aspect ratios on the coupling efficiency between the FMF and FM SOA given, we calculated the overlaps between these two groups of modes after suitable magnifications. Two scenarios were considered. First is equal magnification in horizontal and vertical directions, as in the case of our experiment using a pair of objective lenses. The second is unequal magnification realized by using the combination an objective lens and a cylindrical lens. The coupling matrices for these two cases when the magnifications were optimized to maximize the coupling efficiency for the fundamental mode are as follows:

\[
\begin{bmatrix}
-2.67 & -49.3 & -50.7 & -41.9 \\
-64.2 & -4.32 & -49.8 & -66.1 \\
-53.3 & -54.5 & -4.23 & -43.3 \\
-92.0 & -64.8 & -45.9 & -4.18 \\
\end{bmatrix}_{eq} \quad \begin{bmatrix}
-0.12 & -38.8 & -48.6 & -51.5 \\
-42.6 & -0.28 & -45.7 & -62.6 \\
-49.4 & -50.7 & -0.32 & -27.5 \\
-84.3 & -60.2 & -33.7 & -0.40 \\
\end{bmatrix}_{uneq}
\]

The subscript denotes equal magnification or unequal magnification. The first to the last numbers in diagonal correspond to overlap integrals between \(E_{11}\) and \(LP_{01}\), \(E_{12}\) and \(LP_{11b}\), \(E_{21}\) and \(LP_{11a}\), \(E_{22}\) and \(LP_{21a}\). The non-diagonal element \((i,j)\) represents mode crosstalk from mode \(j\) to mode \(i\), where \(i\) denotes \(E_{11}, E_{12}, E_{21},\) and \(E_{22}\), \(j\) denotes \(LP_{01}, LP_{11b}, LP_{11a},\) and \(LP_{21a}\). Perfect alignment without any offset is assumed.

We can see that the mismatch in aspect ratios reduces the coupling efficiency (diagonal elements) in the equal magnification case while the coupling efficiency reaches near unity if we employ mode-shape matching using unequal magnification. Mode crosstalk levels (off-diagonal elements) are low for both cases. This is because all modes are either symmetric (\(E_{11}\)) or antisymmetric (\(E_{12}, E_{21},\) and \(E_{22}\)). The overlap integrals of different modes in the active region are negligible if there were no misalignments. But in experiments, unavoidable misalignments
would increase mode crosstalk. The mode profiles of FW SOAs have better overlap with those of few-mode elliptical core fibers in comparison with circular FMFs, due to a better match of the aspect ratios.

2.6. Conclusion

We successfully demonstrated the first few-mode semiconductor optical amplifier, supporting up to four waveguide modes. The chip was carefully designed and the quantum wells were strategically placed in the intrinsic layer to allow for equalized gain for all four modes with uniform pumping. Although this “proof of concept” FM SOA was fully functional, many improvements can be made to the design and fabrication in order to achieve less optical and electrical leakage. In the future, we intend to fabricate FM SOAs that are not polarization dependent, by using strained quantum wells. Furthermore, we intend to control the horizontal placement of the quantum wells by using selective area growth and quantum well intermixing. We envision FM SOAs will not only find applications in SDM but also many of the linear and nonlinear optical phenomena that was explored in single-mode SOAs.
CHAPTER 3:  MODE CONVERSION IN FMSOA USING FOUR-WAVE MIXING

3.1.  Introduction

The adoption of optical fibers in communication systems resulted in an explosive growth of the communication speed and unprecedented decrease in transmission cost. The most advanced electrical coaxial cable developed in the 1970s had a bit rate of 274 Mb/s with a distance reach limited to about 1 km [16]. The limited reach of this coaxial cable resulted in a relatively high operation cost since repeaters had to be installed and maintained every 1 km. The bit rate of a single-mode optical fiber, on the other hand, is in the order of hundreds of Tb/s with a reach about 100 km [3]. This high capacity of the optical fibers allowed for a rapid spread of multimedia applications, such as video streaming, high-definition TV, online education, and social media; which significantly reshaped our communities.

Signal processing speeds, meanwhile, lagged far behind as most of the currently deployed processors in telecommunication systems still use electronic digital signal processors (DSPs). The use of DSP for optical signals requires optical-to-electrical (OE) and electrical-to-optical (EO) conversions, which delay the transmission of the data. Furthermore, the use of DSP limits the processing speed to the electronic sampling rate [17]. With the recent advancements in optics and photonics, such as the development of coherent detection, nonlinear optical materials, and photonic integrated circuits (PIC), and the utilization of various optical domains, the scientific community has directed a lot of attention to all-optical signal processors (AOSPs). Not only can AOSPs eliminate the delay induced by the OE and EO conversion, but AOSPs can also operate at much higher processing speed than DSPs. Most AOSPs function by utilizing the optical
nonlinearities of different materials. The response time of many nonlinearities is in the tens of picoseconds or femtoseconds range. Another advantage of AOSPs is that, for many applications, they do not need to operate at the same bit rate as the transmitted signal. For instance, an all-optical wavelength converter (AOWC) based on four-wave mixing (FWM) can convert the carrier frequency of a stream of optical pulses to a different carrier frequency using a nonlinear material and a continuous wave (CW) laser pump [18]. Therefore, the high speed, low delay, and analog behavior of the AOSP make it an attractive option for many applications.

However, high power consumption and low integrability can limit the spread of many AOSP to various applications. When considering the power consumption of an AOSP, we should account for both the optical power of the controlling signals and the electrical power consumption of the device. The power requirement for AOSPs can be high since most nonlinearities are intensity dependent. Very efficient AOSP using optical fibers is demonstrated and utilized in many applications. Optical fiber AOSPs have significant advantages over DSPs for many applications. However, they are bulky and lack the integrability of DSP, limiting their usability for many applications. Furthermore, the well-matured electronics signal processing technology can randomly access a massive amount of memory.

In this chapter, we demonstrate an efficient all-optical mode converter using the inter-modal four-wave mixing (FWM) process in the FM SOA. The high efficiency and the compact size of the developed converter make the converter an appealing platform for AOSP.
3.2. Nonlinear Process for All-Optical Signal Processing

Optical signal processing has been demonstrated using many physical phenomena. Among these phenomena are optical nonlinearities in passive waveguides, such as optical fibers and silicon waveguides, and gain and refractive index nonlinearities of optical amplifiers, such as SOAs. AOSPs based on optical nonlinearities in passive waveguides exploit the nonlinear atomic polarization response of the waveguiding materials to optical waves [19]. The atomic polarization \( P(t) \) of isotropic material with an instantaneous dielectric response is related to the electrical field \( E(t) \) by:

\[
P(t) = \varepsilon_0 \left[ \chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \ldots \right]
\]

where \( \varepsilon_0 \) is the permittivity at vacuum and \( \chi^{(i)} \) is the \( i \)-th order optical susceptibilities. The first-order susceptibility \( \chi^{(1)} \) is related to the refractive index and absorption of the material. The second-order susceptibility \( \chi^{(2)} \) is a property of non-centrosymmetric materials and is exploited in few applications such as electro-optic modulators [19]. More interestingly for optical fibers and Si waveguides, the third-order susceptibility \( \chi^{(3)} \) is responsible for many nonlinear optical effects, such as self-phase modulation, two-photon absorption, and four-wave mixing (FWM) [18].

For an active SOAs, on the other hand, the injection of a high-intensity optical signal saturates the gain by depleting the electrical carriers. This depletion of the carriers results in a change of the refractive index in the SOA. This optically-induced change of the refractive index is the physical phenomena behind most SOA based AOSP. An SOA AOSP employs either an optical interferometric configuration or the FWM process in the SOA. A generic block diagram of an AOSP using SOA interferometric gate is shown in figure 3-1 as an example [20]. A splitter
is used to direct the clock signal, CLK, to both arms of the interferometer. Nonlinear mediums, such as SOAs, are placed at each arm. The refractive indexes of the nonlinear mediums are sensitive to the controlling signals, A and B. When both A and B signals are on, the nonlinear mediums are designed to induce a $\pi$-phase difference between the two clock signals, resulting in an XOR-gate behavior of the combined output clock signal. FWM in SOA, meanwhile, is caused by the interaction of different waves and the SOA. The FWM in SOA is the focus of this chapter and described in the next section.

Figure 3-1: the generic block diagram of an XOR gate using a nonlinear medium.
3.3. Four-Wave Mixing in a Single-Mode SOA

Four-wave mixing (FWM) in single-mode (SM) semiconductor optical amplifiers (SOAs) has been well demonstrated as a practical tool for signal processing. This is, in part, due to the high nonlinearities, sufficiently broad gain spectrum, low cost, and low power consumption of SOAs compared to fiber-based optical amplifiers [21]–[26]. The in-study nonlinearity of the SOA arises from the interactions between multiple waves and the carriers in the active region of the SOA [27]–[29]. When two waves with different frequencies ($\omega_{\text{pump}}$ and $\omega_{\text{probe}}$) are propagating in an SOA, the interference between the two waves would modulate the intensity by $\Delta \omega = \omega_{\text{pump}} - \omega_{\text{probe}}$ according to:

$$I(x, y, z, t) \propto \left| E_{\text{pump}}(x, y) \cos(\omega_{\text{pump}} t - \beta_{\text{pump}} z) + E_{\text{probe}}(x, y) \cos(\omega_{\text{probe}} t - \beta_{\text{probe}} z) \right|^2$$

$$= \frac{E_{\text{pump}}^2(x, y) + E_{\text{probe}}^2(x, y)}{2} + E_{\text{pump}}(x, y)E_{\text{probe}}(x, y) \cos(\Delta \omega t - \Delta \beta z)$$

(3-2)

where $E_{\text{pump}}$ and $E_{\text{probe}}$ are the electrical field of the pump and the probe, respectively. $\beta_{\text{pump}}$ and $\beta_{\text{pump}}$ are the propagation constant of the pump and the probe, respectively. $\Delta \beta = \beta_{\text{pump}} - \beta_{\text{probe}}$, and $\Delta \omega = \omega_{\text{pump}} - \omega_{\text{probe}}$. The high-frequency component of the interference was ignored in (3-2) since it is much faster than the response rate of the carriers in the SOA. In an SOA, high intensities significantly deplete the carriers and create a nonlinear gain and refractive response. Due to the intensity-induced carrier depletion, the carriers will have similar but inverted modulation patterns in the active region (fig. 3-2), which creates an inverted refractive index modulation pattern, a.k.a a grating. The FWM signals diffracted from the dynamic grating acquire new frequencies at $\omega_{\text{FWM}} = \omega \pm \Delta \omega$. 

30
However, the FMW efficiency drops significantly if the frequency detuning between the probe and pump ($\Delta \omega$) is larger than 10 GHz. This drop is due to the limited interband carrier transition time $\tau$. Although spectral-hole burning and carrier heating have much faster transition times, the strengths of these intraband transitions are orders-of-magnitude lower than that of the interband transition. Consequently, highly efficient FWM in SM SOA has only been achieved for frequency detunings within tens of GHz, which is insufficient for high-speed signal processing. Introducing the spatial degree of freedom in signal processing, by using four-wave mixing in a few-mode SOA, could address this issue.

Figure 3-2: a normalized intensity pattern and the carrier density pattern induced in SM SOA due to the FWM process.
3.4. **Four-Wave Mixing in a Few-Mode SOA**

An FM SOA adds a new degree of freedom in the FWM process. Not only we can lunch waves with different frequencies in an FM SOA, but we can also lunch waves with modes. Each mode has a different propagation constant \( \beta_{\text{mode}} \). According to equation (3-2), injecting two waves with the same frequency but different mode-number would modulate the intensity in the FM SOA as a function of distance, not time. Like SM SOA, the modulated intensity will modulate the carriers and creates a gain and index gratings. However, unlike the SM SOA, these gratings are static in time. A recent study showed that few-mode (FM) degenerate FWM, involving the interaction of two transverse modes on two wavelengths, exhibit high conversion efficiencies over a broad bandwidth in FM SOAs [9].

A schematic of an FM SOA is shown in figure 3-3. As mentioned earlier, the FM SOA differs from an SM SOA by having a larger guiding/active layer that supports several spatial modes. The size of the SM SOA is shown in the figure for comparison. The active region is a thin layer of an intrinsic semiconductor on top of an n-type semiconductor substrate and covered by a p-type semiconductor cladding. This layer doping structure creates the p-i-n structure needed to provide the gain of the SOA. Here, the active region is simplified as a rectangular waveguide (brown) surrounded by homogeneous cladding (light blue).
Figure 3-3: Schematic of a simplified FM SOA with a larger cross-section of the active region (brown) compared with that of an SM SOA (white dashed rectangle). Images beside demonstrate the variation of the optical intensity composed of $E_{11}$ and $E_{21}$ mode in the transverse plane of the active region at different positions along the FMSOA. The gain of SOA is neglected for simplicity.

Figure 3-3 also show a set of intensity patterns. These images show the intensity profile in the transverse plane at different longitudinal positions when $E_{11}$ and $E_{21}$ modes are launched into the FM SOA. The gain of the SOA is neglected for simplicity. The intensity pattern varies periodically along the SOA due to the accumulated phase shift difference between the two modes of different propagation speeds. Since the two modes are coherent, the changing of phase shift between them results in intensity pattern variations. This spatially varying temporally-static pattern, which can’t be observed in SMSOAs, offers unique mode selective abilities, i.e., only specific modes strongly interact with a certain carrier pattern.

The periodicity or beat length is typically several tens of microns and calculated by $L_b = \frac{\lambda}{n_{1,\text{eff}} - n_{2,\text{eff}}}$, where $\lambda$ is the optical carrier wavelength, and $n_{1,\text{eff}}$ and $n_{2,\text{eff}}$ are the effective
indeces of the two modes. This carrier grating, in forms of a gain and phase grating, efficiently diffracts certain incoming waves, which satisfy both the non-zero overlap integral over the transverse plane and phase matching conditions.

Because the nonlinear interactions in FM SOA are mediated by static carrier gratings, which are formed by carrier-density modulation due to the beating of two pump modes at the same wavelength, the FWM efficiency is not limited by the interband transition time. The FWM in FM SOA was modeled in [9] using the carrier rate equation and the nonlinear Maxwell’s equation. The coupled-mode mode equation obtained for FM SOA is:

\[
\frac{\partial A^\mu_m}{\partial z} = \frac{\alpha^\mu_m - \alpha^\mu_{int}}{2} A^\mu_m + \sum_{\nu} \kappa_{\nu m}^{\mu \nu} A^{\nu}_m + \sum_{n} \sum_{\nu} \kappa_{nm}^{\mu \nu} A^{\nu}_n
\]  

(3-3)

where \( A^\mu_m \) is the complex amplitude of a wave \( A_{\mu}(z, \omega_m) \) with \( \mu \) is the mode number and \( \omega_m \) is the frequency. Equation (3-3) have three terms. The first term represents the internal loss (\( \alpha^\mu_{int} \)) and modal gain (\( g^\mu_m \)) of each mode \( \mu \) at a frequency \( \omega_m \), and they can be calculated using:

\[
\alpha^\mu_{int} = \alpha_a \Gamma^\mu_m + \alpha_c (1 - \Gamma^\mu_m) + \alpha_s
\]  

(3-4)

\[
g^\mu_m = \frac{g_{mt}(1+i\alpha)}{1+I_{dc}} \Gamma^\mu_m
\]  

(3-5)

where \( \alpha_a, \alpha_c, \alpha_s \) are the loss of the active region, cladding, and guiding material, respectively, \( \alpha \) is the line enhancement factor, \( \Gamma^\mu_m \) is the mode confinement factor of a wave of mode \( \mu \) and frequency \( \omega_m \), and \( I_{dc} \) is the time-averaged normalized optical intensity at \( \omega_m \). The second term demonstrates the coupling between waves with different modes (\( \nu \) and \( \mu \)) but on the same frequency (\( \omega_m \)). The coupling coefficient (\( \kappa_{nm}^{\mu \nu} \)) is:
\[
\kappa_{mn}^{\mu\nu} = -\frac{g_m(1+i\alpha)\beta_m^\mu}{2(1+i\delta)^2\beta_m^\mu} \sum_n \sum_\sigma \sum_\xi \Gamma_{mnln}^{\mu\xi\sigma\nu} \Lambda_n^\sigma \Lambda_l^\xi \exp[i\Delta\beta_{mnln}^{\mu\xi\sigma\nu}z] 
\]

where \(\beta_m^\mu\) is the propagation constant of mode \(\mu\) at frequency \(\omega_m\), \(\Gamma_{mnln}^{\mu\xi\sigma\nu}\) is the normalized four-wave overlap integrals across the active region, \(I_{n,\text{sat}}\) is the saturation intensity, and \(\Delta\beta_{mnln}^{\mu\xi\sigma\nu}\) is phase mismatch of the involved modes. Finally, the third term demonstrates the coupling between waves with different modes \((\nu\) and \(\mu\)) and different frequencies \((\omega_m\) and \(\omega_n\)). The coupling coefficient \((\kappa_{mn}^{\mu\nu})\) is

\[
\kappa_{mn}^{\mu\nu} = -\frac{g_m(1+i\alpha)\beta_m^\mu}{2(1+i\delta)^2\beta_m^\mu} \sum_k \sum_{l \neq k} \sum_\sigma \sum_\xi \Gamma_{mlkn}^{\mu\xi\sigma\nu} \Lambda_n^\sigma \Lambda_l^\xi \exp[i\Delta\beta_{mlkn}^{\mu\xi\sigma\nu}z] 
\]

where \(\Gamma_{mlkn}^{\mu\xi\sigma\nu}\) is the normalized four-wave overlap integrals across the active region, \(I_{kl,\text{sat}}\) is the saturation intensity, and \(\Delta\beta_{mlkn}^{\mu\xi\sigma\nu}\) is phase mismatch of the involved modes. Few assumptions were used to driving the model, which limit the model to slowly varying signals, compared to the transition time through the FM SOA. The model satisfies most telecommunication signals with less than 50-GHz bandwidth per channel. The group velocity effect on a slowly varying signal is also neglected.

Expressions in (3-2) to (3-7) describe how the mode fields evolve along the FM SOA, experiencing amplification and phase shift governed by the complex modal gain and coupling with other modes diffracted by the carrier grating described by \(\kappa_{mn}^{\mu\nu}\) and \(\kappa_{mn}^{\mu\nu}\). Coupling only occurs between certain modes satisfying energy conservation \(\omega_k - \omega_l + \omega_n - \omega_m = 0\), small phase mismatch \(\Delta\beta \ll 1\) and non-zero effective mode field overlap \(\Gamma \neq 0\). These selection rules are defined as the parallelogram rules.
The mode-selective parallelogram rule (MSPR) is a visual method to describe the mode selection in FM SOAs. In a frequency-mode number plane (fig. 3-4), the MSPR specify that only waves located at the vertices of a parallelogram explicit considerable coupling coefficient. Coupling between the requires first conservation of energy. For waves located at the vertices of a parallelogram, the addition of two diagonal frequencies always equals the addition of the other two diagonal frequencies, indicating energy conservation. Second, a considerable coupling between waves requires also small phase mismatch. Waves with similar mode numbers have very close propagation constant $\beta$. The addition of two diagonal mode-numbers always equals the addition of the other two diagonal mode-numbers, indicating an approximate phase matching ($\Delta\beta \ll 1$). Also, a strong mode field overlap arises when the sides of the parallelogram are parallel to the frequency axis.

There are 3 types of parallelograms that represent the 3 different configurations of coupled modes in the F-WN planes. The rectangle in Fig. 3-4(a) denotes the coupled modes involving two distinct frequencies, and the parallelograms in Fig. 3-4(b) and 3-4(c) involving three and four frequencies, respectively. They are called degenerate FWM, partial degenerate FWM and non-degenerate FWM, respectively. As a special case, mode couplings in SM SOAs can be treated in the same way that parallelograms are reduced to horizontal line segments, shown in Fig. 3-4(d) and 3-4(e). Similarly, there are single mode degenerate and non-degenerate FWMs. The mode number can be generalized to a negative value to account for counter propagation waves, shown in Fig. 3-4(f) and 3-4(g). The MSPR rule tells us that the mode number is closed or waves with a new mode can’t be generated in a narrow frequency range by using FWM.
Figure 3-4: Illustrations of mode selective parallelogram rule in frequency-mode number planes. Any wave is represented by a point in the frequency-mode number plane. Any waves at the four vertices of a parallelogram effectively interact with each other. Based on the shape of a parallelogram, the waves interactions are classified as: (a) few-mode degenerate FWM, (b) few-mode partial degenerate FWM and (c) few-mode non-degenerate FWM. Single-mode FWM such as: (d) degenerate FWM and (e) non-degenerate FWM are special cases of the few-mode FWMs. Generalized mode number to negative can account for counter-propagation FWM such as: (f) few-mode counter-propagation FWM and (g) single-mode counter-propagation FWM.
As mentioned earlier, the FWM efficiency drops significantly for SM FMSA if the frequency detuning between the probe and pump ($\Delta \omega$) is larger than 10 GHz. The theoretically predicted FWM efficiency in FM SOA, on the other hand, remains almost constant over hundreds of GHz and is two to three orders of magnitude stronger than that in SM SOAs. In the following section, we report the first observation and experimental characterization of FM degenerate FWM in an FM SOA.

3.5. Devices Structure and Fabrication

The FM SOA was fabricated using a commercial n-doped InP wafer with InAlGaAs MQWs operating at 1550 nm (table 3-1). The intrinsic active region consists of a graded-index separate-confinement heterostructure containing 6-nm-thick quantum wells and 9-nm-thick barriers. The p-doped top layers consist of thin InP (50 nm) and InGaAsP (15 nm) etch stop layers, a 1500-nm-thick InP cladding layer and a 50-nm-thick InGaAsP and a 150-nm-thick InGaAs contact layers.

A thin film of SiNx was grown on the wafer using plasma-enhanced chemical vapor deposition, and 8 µm-wide waveguide stripes were patterned into the film using contact-mask photolithography and reactive-ion etching (RIE). The waveguide stripes were patterned with 4°-tilt to the cleaving facet to reduce the reflection from the facets and prevent lasing. The SiNx stripes were used as masks for wet etching the cladding and active layers. The wet etching of the active layer reduced the width of the waveguides to about 4 µm. After removing the SiNx stripes, a 3-µm-thick film of Benzocyclobutene (BCB) was spin-coated and cured covering the waveguide structure. The BCB film is thinned by O2 reactive-ion etching until the very top of the waveguide is exposed. Negative photoresist was used to shape the top n-contact metals, that were...
deposited using vacuum thermal evaporation. The substrate of the wafer was lapped and polished and the p-contact metals were thermally evaporated on the back side. The two facets of the FM SOAs were cleaved and the sample was mounted for testing. The FM SOAs can support the $E_{11}$, $E_{12}$, and $E_{13}$ (weakly-guided) modes.

Table 3-1: Epitaxial layer structure of the InAlGaAs MQW wafer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Doping (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-Contact</td>
<td>InGaAs</td>
<td>150</td>
<td>$P = &gt;1 \times 10^{19}$</td>
</tr>
<tr>
<td>Etch Control</td>
<td>InGaAsP (1.5Q)</td>
<td>25</td>
<td>$P = &gt;3 \times 10^{18}$</td>
</tr>
<tr>
<td></td>
<td>InGaAsP (1.3Q)</td>
<td>25</td>
<td>$P = &gt;3 \times 10^{18}$</td>
</tr>
<tr>
<td>Top cladding</td>
<td>InP</td>
<td>1500</td>
<td>$P = 0.5-1.5 \times 10^{18}$</td>
</tr>
<tr>
<td>Etch Control</td>
<td>InGaAsP (1.1Q~1.15Q)</td>
<td>15</td>
<td>$P = 5 \times 10^{17}$</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>50</td>
<td>$P = 5 \times 10^{17}$</td>
</tr>
<tr>
<td>Guiding layers</td>
<td>U-InAlAs</td>
<td>50</td>
<td>Undoped</td>
</tr>
<tr>
<td></td>
<td>U-GRIN-InAlGaAs</td>
<td>100</td>
<td>Undoped</td>
</tr>
<tr>
<td>MQW</td>
<td>QWs/Barriers</td>
<td>5-6/9</td>
<td>Undoped</td>
</tr>
<tr>
<td>Guiding layers</td>
<td>U-GRIN-InAlGaAs</td>
<td>100</td>
<td>Undoped</td>
</tr>
<tr>
<td>Lower Cladding</td>
<td>InAlAs</td>
<td>140</td>
<td>$N = 8 \times 10^{17}$</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>50</td>
<td>$N = 1 \times 10^{18}$</td>
</tr>
<tr>
<td>Substrate</td>
<td>InP</td>
<td></td>
<td>$N = 2-8 \times 10^{18}$</td>
</tr>
</tbody>
</table>
Figure 3-5: Schematics of the InAlGaAs MQW bandgap diagram grown using MOCVD

Figure 3-6: Schematic of the InAlGaAs MQW FM SOA with n-contact propping the full ridge-waveguides.

Upon testing the fabricated FM SOA, the lasing threshold of a 1-mm-long device was found to be 45 mA. Therefore, the devices will not operate as SOA unless the reflections from the facets are reduced. One option to reduce the reflection is to increase the tilt angle of the waveguides. However, doing so will significantly increase the difficulty of launching the pure modes into the FM SOA. An efficient antireflection coating requires depositing a thin film with a
precise refractive index and film thickness, which can be challenging using the current facilities in the cleanroom. Alternatively, a new FM SOA was fabricated with an additional absorbing section. The absorption section allows for the injection of high-density carriers in the active section while absorbing most of the waves reflected by the output facet.

The previously described fabrication process was followed to fabricate the waveguide structure. However, after spin-coating and curing the BCB, each waveguide was divided into two equal sections. In one section, the BCB film was thinned down, using RIE, until the top of the waveguides were uncovered. Meanwhile, the BCB film was preserved (unetched) on the other section (Fig. 3-1). The metal contact was applied next. As shown in Fig. 3-1, the n-contact metal only addresses the uncovered side of the FM SOAs while the BCB film isolates the other side. The isolated section of the FM SOA was used to absorb the light and prevent the lasing at high injection current levels.

Figure 3-7: Schematic of the InAlGaAs MQW FM SOA with n-contact propping half the ridge-waveguides while the BCB layer is isolating the other half of the waveguides. The n-contact is removed from the schematic of one FM SOA to show the covered features.
3.6. **Experiment Setup and Results**

The setup shown in Figure 3-2 was used to characterize the FWM process in the fabricated FM SOA. A 1550-nm laser was used to excite a probe wave and an amplified tunable laser was used to excite pump waves. The output of each laser is collimated by a couple of 10× microscope objective lenses, and a phase plate was used in the path of each laser beam to spatially shape the desired modes for launching into the FM SOA waveguide. If no phase plate was used, the beam excites the fundamental $E_{11}$ mode of the SOA. When a phase plate was aligned to the center of the beam, it excites the higher order $E_{21}$ mode. Meanwhile, slightly misaligning the phase plate in the horizontal direction excites both $E_{11}$ and $E_{21}$ modes. The beams were combined using a free-space beam splitter and passed through a TE polarizer to exclusively excite TE modes into the FM SOA using a 40× microscope objective lens. The large magnification of the launching lens compared to the collimating lenses was used to transform the mode size of the single mode fiber (SMF) to match that of the FM SOA. The output of the FM SOA is collimated using another 40× objective lens and most of the amplified spontaneous emission and stray beams are blocked using a narrow bandpass filter and an aperture. A beam-splitter was used to direct the output of the FM SOA to an IR camera and a SMF through a 10× objective lens. Only the $E_{11}$ mode of the FM SOA is coupled into the SMF, which is connected to an optical spectrum analyzer (OSA). To analyze the $E_{21}$ mode of the FM SOA, a phase plate was placed by the output of the FM SOA to reshape the $E_{21}$ mode to match the fundamental mode of the SMF while deforming the $E_{11}$ mode as shown in Figure 3-3.
Figure 3-8: Schematic of the experimental setup used to characterize FWM in the FM SOA.

We first searched for the best bias current by injecting the probe and pumps in the $E_{11}$ mode and observing the FWM component in the output spectrum. The wavelength difference between the probe and pump was set at $\Delta \lambda = \lambda_{\text{pump}} - \lambda_{\text{probe}} = 0.4$ nm. Figure 3-4 and figure 3-5 show the optical spectra of the output of the FM SOA when 90 mA and 115 mA bias currents were applied to the SOA. A SM non-degenerate FWM signal was generated at $\lambda_1 = \lambda_{\text{probe}} - \Delta \lambda$ and $\lambda_2 = \lambda_{\text{probe}} + 2\Delta \lambda$ with about 3 dB gain. For the following FM FWM experiment, we set the current to 96 mA. Even though we could not observe a SM FWM signal with a current bias less than 100 mA, a bias of 96 mA was sufficient for FM FWM.
Figure 3-9: Output of the FM SOA, where the dotted circles represent the part of modes overlapping the SMF.

Figure 3-10: The output spectra of the InAlGaAs MQW FM SOA when two fundamental-mode waves were lunched into the FM SOA at bias currents of 90 mA.
Next, we investigated FM degenerate FWM by injecting the $E_{11}$ and $E_{21}$ pump waves at $\lambda_{pump} = 1551$ nm and the $E_{11}$ probe at $\lambda_{probe} = 1550.6$ nm into the FM SOA. This was accomplished by inserting a phase plate after the collimating lens in the pump path. The mode and wavelength of the waves involved in the FM degenerate FWM are shown in Fig. 3-6, where a $E_{21}$ wave at the probe wavelength $\lambda_{probe}$ was generated as the product of the FWM. By placing or removing the output phase plate to examine the output spectra of the $E_{11}$ or $E_{21}$ modes, respectively, we record the output intensity of the probe, the converted signal, and the two pump modes using the OSA when the total input power of the two pumps varied from 7 dBm to 18 dBm. The results are shown in Fig. 3-7. As predicted in [9], the FWM signal power initially decreased while the probe wave was amplified when the input pump power is increased from 7 dBm to 10 dBm. For pump powers between 10 dBm and 13 dBm, the FWM signal experiences
amplification while the probe wave experiences a reduction of power. Beyond 10 dBm of input pump power, the intensity of all waves involved in the FWM process increased. These behaviors are results of co-existence of the gain and refractive-index grating. The latter arises due to a non-zero linewidth enhancement factor. The scattered waves by these two gratings can interfere constructively or destructively for different waves in certain conditions. For the same input pump and probe, the SM FMW component is -42.5 dBm and the FM FWM component is -32.5 dBm. Therefore, the FM FWM conversion efficiency is much higher than that of the SM FMW. Figure 3-8 shows the power of the FWM signal as a function of frequency detuning. As we expect, the power is almost constant within ±400-GHz frequency detuning range, as the efficiency of FM degenerate FWM is independent of the carrier transition time. Moreover, the power in negative frequency detuning ($f_{\text{probe}}-f_{\text{pump}}<0$) is about 2 dB stronger than that in the positive side. This phenomenon originates from the non-zero linewidth enhancement factor and was predicted in [11].

Figure 3-12: Illustration of exited and detected waves for the FM SOA mode conversion experiment.
Figure 3-13: intensity of the output pumps, probe and converted signal as function of injected pumps.

Figure 3-14: intensity of converted signal as a function of pump and probe frequency detuning.
3.7. Conclusion

We demonstrate few-mode degenerate FWM in FM SOAs for the first time. The FM degenerate FWM efficiency is much higher than that in SM SOAs and is almost constant over ±400 GHz detuning. These features suggest a promising potential of FM SOA for high-speed signal processing.
CHAPTER 4: MODE CONVERSION IN A SEMICONDUCTOR DIRECTIONAL COUPLER BY ENCIRCLING THE EXCEPTIONAL POINT

4.1. Parity-Time Symmetry and Exceptional Point

Traditionally, few postulates were defined as the foundations of quantum mechanics [30], [31]. One of these postulates is the requirement that the energy quantum operators are Hermitian. The Hermitian requirement is a mathematical (not physical) requirement. It ensures that the energy quantum operator, called Hamiltonian, have real and positive eigenvalues. Eigenvalues are the observables, or measurable variables, of the quantum system. An operator ($\hat{O}$) is called Hermitian if it satisfies:

$$\hat{O}^\dagger = [\hat{O}^T]^* = \hat{O} \quad (4-1)$$

where $\dagger$ is the Dirac Hermitian conjugation and it represents the transpose and complex conjugation of the matrix. However, a new family of Hamiltonians was discovered recently to have real and positive eigenvalues without the Hermitian requirement [32]. These non-Hermitian operators are called Parity-Time ($\hat{P}\hat{T}$) symmetric Hamiltonians. In $\hat{P}\hat{T}$-symmetric Hamiltonians, the Hermitian requirement of the operator is replaced with the more general $\hat{P}\hat{T}$-symmetric requirement:

$$\hat{O}^{\hat{P}\hat{T}} = \hat{O} \quad (4-2)$$

The parity operator ($\hat{P}$) flips the sign of the space operator ($\hat{x}$) and momentum operator ($\hat{p}$):

$$\hat{P}\hat{x}\hat{P} = -\hat{x} \quad (4-3)$$

$$\hat{P}\hat{p}\hat{P} = -\hat{p} \quad (4-4)$$
Meanwhile, the time-reversal operator ($\hat{T}$) flips only the sign of the momentum operator ($\hat{p}$):

\[
\hat{T}\hat{x}\hat{T} = \hat{x}
\]

\[
\hat{T}\hat{p}\hat{T} = -\hat{p}
\]

The development of non-Hermitian quantum mechanics has several advantages [33]. Among these advantages is the fact that the non-Hermitian quantum mechanics allows the inclusion of many phenomena into the quantum languages. For example, the dissipative process, such as radioactive decay or optical loss, cannot be fundamentally included in the Hermitian quantum mechanics formalization due to its violation of the conservation of probability. Traditionally, these processes were treated as perturbations [34]. However, non-Hermitian quantum mechanics allows for complex Hamiltonian. Thus, non-Hermitian formalizations can be used to study such systems.

The Schrödinger equation defines the wavefunction evolution in the a quantum system, and it is defined by:

\[
i \frac{\partial}{\partial t} \psi = \hat{H}\psi
\]

where $\hat{H}$ is the Hamiltonian of the system. For time-independent potential:

\[
\hat{H} = \frac{\hat{p}^2}{2} + V(\hat{x})
\]

where $V(\hat{x})$ is the potential. For a $\hat{P}\hat{T}$-symmetric system, the commutation requirement between $\hat{H}$ and $\hat{P}\hat{T}$ ($[\hat{H}, \hat{P}\hat{T}] = 0$) implies that:

\[
V^*(-x) = V(x)
\]
This means that in a $\hat{\mathcal{PT}}$-symmetric system, the real part and imaginary part of the potential must be even function and odd, respectively.

The use of non-Hermitian formalizations for optical waveguide can be rationalized by looking at the isomorphism between the Schrodinger equation for quantum mechanics and the Maxwell equation under the paraxial approximation [32]. The one-dimensional time-independent Schrödinger equation is defined by [35]:

$$
\left[ -\frac{1}{2} \frac{\partial^2}{\partial x^2} + V(x) \right] \Psi(x) = E \Psi(x)
$$

(4-10)

where $V(x)$ is the potential, $E$ is the energy and $\Psi(x)$ is the time-independent wavefunction. Meanwhile, the Maxwell wave equation of an optical mode in a 1-dimensional waveguide under paraxial approximation is described by:

$$
\left[ \frac{\partial^2}{\partial x^2} + k^2 n(x)^2 \right] E_y(x) = \beta^2 E_y(x)
$$

(4-11)

where $k = 2\pi/\lambda$ is the free space propagation constant, $n(x) = n_{Re}(x) + in_{Im}(x)$ is the complex index of the guiding material, $n_{Re}(x)$ is the refractive index of the guiding material, $n_{Im}(x)$ is the gain/loss of the guiding material, and $\beta$ is the propagation constant of the mode. Looking at equations (4-7) and (4-8), the analogy between the time-independent Schrödinger equation and the Maxwell wave equation is clear. Since non-Hermitian allows for complex Hamiltonian (or complex potential), the light propagation in an optical waveguide can be described by the time-independent Schrödinger by setting:

$$
V(x) = -\frac{1}{2} k^2 n(x)^2
$$

(4-12)

and
\[ E = -\frac{1}{2} \beta^2 \]  

(4-13)

However, according to (4-9) and (4-12), the realization of a $\hat{P}\hat{T}$-symmetry in the optical domain requires that the refractive index is an even function of position, while the gain/loss is an odd function of position:

\[ n_{Re}(x) = n_{Re}(-x) \]  

(4-14)

\[ n_{Img}(x) = -n_{Img}(-x) \]  

(4-15)

![Schematic of a standard waveguide coupler.](image)

**Figure 4-1:** Schematic of a standard waveguide coupler.

A $\hat{P}\hat{T}$-symmetric system can be demonstrated using a coupled waveguides system. Figure 4-1 shows a standard coupled waveguide with a coupling coefficient $\kappa$. Ignoring the intrinsic loss of the waveguides, the following 2-level system describes the slow varying evolution dynamics of the slowly varying fields in the waveguides, assuming the time dependence of the electrical field is in the form of $e^{-i\omega t}$:

\[ i \frac{d}{dz} \begin{bmatrix} a \\ b \end{bmatrix} + \begin{bmatrix} 0 & \kappa \\ \kappa & 0 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = 0 \]  

(4-16)
where $a$ and $b$ are the slowly varying fields in both waveguides over the propagation direction $z$, and the Hamiltonian of the system $\hat{H} = \begin{bmatrix} 0 & \kappa \\ \kappa & 0 \end{bmatrix}$. Assuming fields are of the form $\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} e^{i\alpha z}$, the two eigenvalues of (4-16) are $\lambda_{1,2} = \pm \kappa$ and the corresponding eigenvectors are $|1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ (the in-phase supermode), and $|2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ (the out-phase supermode).

The coupled waveguides in figure (4-1) can be translated to the $\hat{P}\hat{T}$-Symmetric regime by adding gain to waveguide $(b)$ and loss to waveguide $(a)$ as shown in figure (4-2). The new Hamiltonian of the system is expressed by $\hat{H} = \begin{bmatrix} -ig & \kappa \\ \kappa & +ig \end{bmatrix}$, where $\pm g$ represent the gain, for positive values, and the loss, for negative values. In this system, we assume that the gain and loss does affect the effective refractive index of the waveguides. Therefore, if we assign the $x$-axis to the axis parallel to the separation between the two waveguides, where $x = 0$ is located at the midpoint between the two waveguides (fig. (4-2), the real part of the refractive index has an even function of $x$ ($n_{Re}(x) = n_{Re}(-x)$), and the imaginary part of the refractive index, the gain or loss, has an odd function $x$ ($n_{Im}(x) = -n_{Im}(-x)$). Thus, the Hamiltonian $\hat{H}$ satisfies the $\hat{P}\hat{T}$ requirement defined in expressions (4-14) and (4-15) and, as a result, have real and positive

Figure 4-2: Schematic of a $\hat{P}\hat{T}$-Symmetric waveguide coupler.
eigenvalues. The following Schrödinger describes the $\hat{P}\hat{T}$-symmetric waveguide coupler:

$$i \frac{d}{dz} \begin{bmatrix} a \\ b \end{bmatrix} + \begin{bmatrix} -ig & \kappa \\ \kappa & +ig \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = 0$$  \hspace{1cm} (4-17)$$

By assuming slowly varying fields of the form $\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} e^{i\lambda z}$, the eigenvalues are be found to be $\lambda_{1,2} = \pm\kappa\cos(\theta)$ where $\theta = \sin^{-1}(g/\kappa)$ when $g < \kappa$. The corresponding eigenvectors are $|1\rangle = \begin{bmatrix} 1 \\ e^{i\theta} \end{bmatrix}$ and $|2\rangle = \begin{bmatrix} 1 \\ -e^{-i\theta} \end{bmatrix}$. Meanwhile when $g > \kappa$, the eigenvalues are found to be $\lambda_{1,2} = \pm\sinh(\theta)$ where $\theta = \cosh^{-1}(g/\kappa)$, which correspond to eigenvectors $|1\rangle = \begin{bmatrix} 1 \\ ie^{-\theta} \end{bmatrix}$ and $|2\rangle = \begin{bmatrix} 1 \\ ie^{\theta} \end{bmatrix}$. The propagation constant of each supermode ($\beta_{1,2}$) deviates from the waveguide’s propagation constant ($\beta_0$) by the eigenvalues ($\beta_{1,2} = \beta_0 + \lambda_{1,2}$).

Looking at the super-modes of the two regimes, $g < \kappa$ and $g > \kappa$, we can observe one of the unique properties of a $\hat{P}\hat{T}$ system. When $g < \kappa$, the intensity is symmetrically divided between the two waveguides ($a$ and $b$) even though waveguide $a$ experiences loss and waveguide $b$ experiences gain. This intensity symmetry is the reason the phenomena is called $\hat{P}\hat{T}$-“symmetric.” However, the symmetry breaks when the gain/loss exceeds the coupling between the two waveguides ($g > \kappa$). At this asymmetric regime, the relative intensity of waveguide $a$ is higher than waveguide $b$ in the first supermode $|1\rangle$, and the relative intensity of waveguide $a$ is lower than waveguide $b$ in the second supermode $|2\rangle$.

A sharp transition between the two regimes occurs at $g = \kappa$. This transition point is called the exceptional point (EP), and it manifests a degeneracy of both eigenvalues ($\lambda_{1,2} = 0$) and eigenvectors ($|1\rangle = |2\rangle = [1 \hspace{7mm} i]^T$). The coalesce of eigenvalues have been observed in
Hermitian systems, and it is called a diabolic point. However, the coalesce of eigenvectors is a unique property of the EP in the $\hat{\rho} \hat{\tau}$-Symmetric system. The EP has been attributed to many unprecedented phenomena. One of these unusual phenomena is the fact that an adiabatic encircling of the EP results in asymmetric behavior. The encircling of an EP of order 2 is devised by manipulating the system parameters to provide a trajectory around the EP. As a result, the output of the system emerges as a single supermode. The final supermode of the system is independent of the input and solely depends on the direction of encirclement; clockwise or counterclockwise.

The chiral effects of encircling the EP has been analytically proven and demonstrated in the microwave domain and passive optical waveguides. In the later, different optical devices were used to demonstrate different encirclement direction around the EP. In this chapter, the chiral behavior is demonstrated in an active waveguide coupler. The waveguide coupler was designed by carefully manipulating the propagation parameters in the coupler along the propagation direction. Counter-propagating waves in the coupler experience opposite encirclement direction around the EP. As a result, different supermode emerges from each facet of the waveguide coupler. Furthermore, the EP encirclement is activated by controlling the injected current to the active waveguide coupler.
4.2. Design and simulation of the Asymmetric Super-Mode Converter

A waveguide coupler is designed to demonstrate the asymmetric behavior associated with the encirclement of the EP. The encirclement of an EP can be achieved by constructing a topological loop around the EP in the real and imaginary plane of the relative propagation constants. A modified version of the $\mathcal{PT}$-symmetric waveguide coupler (previously shown in fig. 4-2) is designed to provide the desired encirclement around the EP. As shown in figure 4-3, the width of the waveguide $a$ is modulated to induce the variation of the real part of the differential propagation constant $\Delta \beta$. Waveguide $a$ is a passive waveguide (the gain is set to zero). Meanwhile, the gain induced in waveguide $b$ gradually increased from zero at two ends of the waveguide and peaks at the center of the waveguide. Figure 4-4 shows the EP in the real and imaginary plane of the relative propagation constants where $\Delta g$ on the x-axis represents the imaginary part of the differential propagation constant, and $\Delta \beta$ represents the real part of the differential propagation constant. Both axes of the plane are normalized to the coupling coefficient ($\kappa$).

![Figure 4-3: Schematic of the waveguide coupler designed to provide an EP encirclement.](image)
Figure 4-4: The EP in the real and imaginary plane of the relative propagation constants and the CW and CCW loops around the EP demonstrated by the waveguide coupler.

Figure 4-4 also shows the propagation parameters at different positions (z) in the waveguide coupler. It is clear that waves propagating in an ascending z-direction (from \( z = 0 \) to \( z = L \)) experience clockwise (CW) encirclement trajectory around the EP. Meanwhile, waves propagating in a descending z-direction (from \( z = L \) to \( z = 0 \)) experience counter-clockwise (CCW) encirclement trajectory around the EP. Therefore, counter-propagating waves in the waveguide coupler will experience asymmetric behaviors, where all the waves at \( z = 0 \) and \( z = L \) will be converted to the \( |1\rangle \) and \( |2\rangle \) supermodes, respectively.

We simulated the chiral phenomena of the EP encircling waveguide coupler using the Runge-Kutta algorithm. The wave evaluation of the waveguide coupler can be described by:
\[
\begin{align*}
\frac{i}{\kappa} \frac{d}{dz} [a] + \left[ \begin{array}{c} \Delta \beta(z) \\ \kappa \\ ig(z) \end{array} \right] [a] = 0
\end{align*}
\] (4-18)

The coupling between the waveguides was set to \( \kappa = 8.5 \, cm^{-1} \), and the length of the coupler was set to \( L = 15 \, mm \) to provide slow encirclement around the EP. To provide the trajectory shown in figure 4-4, the gain and the differential propagation constant were defined by:

\[
\begin{align*}
g(z) &= g_0 [1 - \cos(2\pi z/L)] \\
\Delta \beta(z) &= \Delta \beta_0 \sin(2\pi z/L)
\end{align*}
\] (4-19, 4-20)

where \( g_0 = \Delta \beta_0 = \kappa \). Figure 4-5 shows the gain and the propagation constant as a function of \( z \).

Figure 4-5: The differential propagation constant and the gain used for the simulation of the waveguide coupler.
Figure 4-6: The simulated evolution of the waves with a random initial state in the waveguide coupler. The upper graphs show the a) intensity and b) phase evolutions during CW encirclement around the EP, and the lower graphs show the c) intensity and d) phase evolutions during CCW encirclement.

The Runge-Kutta algorithm can show the evolution of the intensity and phase in each waveguide. Figure 4-6 shows the differential intensity and phase for both the CW and CCW wave propagation when the coupler was exited by a random initial state. Figure 4-6 (a) and (b) shows the CW encirclement around the EP. At the end of the coupler, the relative intensity of the waveguides are \( I_a/I_b = 1 \) and the relative phase is \( \Delta \phi = 0 \). The final eigenstate, or supermode,
of a CW encirclement around the EP is \( |1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \). On the other hand, when the loop takes the opposite CCW encirclement direction around the EP, the output of the waveguide coupler emerges as the \( |2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix} \) supermode. The \( |2\rangle \) supermode is demonstrated by the output relative intensity of \( I_a/I_b = 1 \) and the output relative phase of \( \Delta\phi = \pi \) apparent at the end of the coupler in figure 4-6 (c) and (d).

Figure 4-7: The simulated evolution of the several waves with varying initial state in the waveguide coupler. The upper graphs show the a) intensity and b) phase evolution during CW encirclement around the EP, and the lower graphs show the c) intensity and d) phase evolution during CCW encirclement.
The final states are independent of the intial eigenstate as shown in figure 4-7, where the coupler is lunched with different supermodes with varying differential input phase $\phi_i$ of the exiting supermode $\psi_i = \left[ \frac{1}{\sqrt{2}} e^{i \phi_i} \right]$. The phase difference between the output of both waveguides is always an even multiple of $\pi$ for CW encirclement (fig. 4-7(b)) and an odd multiple of $\pi$ for CCW encirclement (fig. 4-7(d)). Furthermore, the output intensities of both waveguides are equal for CW and CCW encirclements (fig. 4-7 (a), (c)). For any input, the final eigenstates are $|1\rangle = \left[ \begin{array}{c} 1 \\ 1 \end{array} \right]$ when the encirclement direction is CW, and $|2\rangle = \left[ \begin{array}{c} 1 \\ -1 \end{array} \right]$ when the encirclement direction is CCW.

Figure 4-8: The simulated CCW loop around the EP with the color map showing the relative phase acquired as the waves propagate in the coupler.
Figure 4-9: The simulation of a couple of a) CCW loop and b) CW loop that do not enclose the EP.

Figure 4-8 shows the simulated CCW loop around the EP with the color map showing the relative phase acquired as the waves propagate in the coupler ($|\Delta \phi(z)/\pi|$). It is clear that the input eigenstate $\psi_i = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ is transformed into the $|2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ eigenstate by the end of the loop.

When the maximum gain is reduced so that the loop does not enclose the EP, as shown in figure 4-9 (a), the final eigenstate does not is transformed into the $|2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ anymore. The final eigenstate is an arbitrary combination of the $|1\rangle$ and $|2\rangle$ eigenstates. The same behavior is also observed when the loop is CW (fig. 4-9 (b)). This shows that the chiral behaviors require the encirclement of the EP and can be activated or deactivated by controlling the gain of the active waveguide in the coupler.
We used the commercially supplied InAlGaAs MQW (table 3-1) to demonstrate the EP encircling waveguide coupler experimentally. The coupler is designed by setting the width of the waveguides to $w_0 = 4 \, \mu m$ with a $w_s = 3 \, \mu m$ separation between the two waveguides. The waveguides had a ridge waveguide structure. The coupling coefficient was controlled by controlling the ridge depth ($h$) of the waveguides (fig. 4-10). RSoft photonic design software from Synopsys was used to simulate the mode profile of the waveguides and the coupling coefficient of the coupler. As shown in figure 4-11 and figure 4-12, we found that an optimum ridge depth of $h = 1.07 \, \mu m$ would result in a single-mode operation and a coupling coefficient of $\kappa = 8.537 \, cm^{-1}$.
Figure 4-11: The simulated mode profile of a 4μm-wide InAlGaAs MQW waveguide with a ridge depth of 1.07 μm.

Figure 4-12: The simulated coupling of two 4μm-wide InAlGaAs MQW waveguides spaced by 3μm and have a ridge depth of 1.07 μm.
The propagation constant of the passive waveguide (waveguide $a$) was modulated by modulating the width of the waveguide. Rsoft was used to simulate the effective refractive index ($n_{eff}(w)$) of the waveguide with different widths, as shown in figure 4-13. The differential propagation constants normalized to the coupling coefficient were calculated and plotted in figure 4-14. It is clear that a modulation depth of $0.5\mu m$ for the width of the passive waveguide is sufficient to induce the $\Delta\beta$ required to encompass the EP.

![Figure 4-13: The effective index of the InAlGaAs MQW waveguide as a function of the width.](image-url)
Figure 4-14: The relative propagation constants normalized to the coupling coefficient as a function of width.

The gain profile for the active waveguide (waveguide b) can be structured by manipulating the shape of the metal contact and the position of the probes injecting the current to the device. The procedure used to control the gain will be discussed in details in a later section. However, during our simulations, we assumed that the current biasing does alter the real part of the propagation constant. As we saw in chapter 2, the injection of free carriers affects the refractive index of the material significantly. The change of the refractive index due to carrier injection would significantly deform the topological loop around the EP. To eliminate the carrier-induced differential refractive index, we intermixed the quantum wells of the passive waveguide and biased the passive waveguide with the same current as the active waveguide. Quantum well intermixing (QWI) is a post-growth technique to expand the bandgap of the well.
Thus, QWI the passive waveguide will shift the operation wavelength of the wells to lower
wavelength and eliminate the absorption of photons at the original wavelength. As we will see in
the next section, QWI can be used to shift the gain of the InAlGaAs MQW to around $\lambda_{passive} =
1.45 \, \mu m$. Biasing the intermixing passive waveguide does not induce any gain for our
wavelength-of-interest ($\lambda_{active} = 1.55 \, \mu m$). Nonetheless, the biased intermixing waveguide will
experience a carrier-induced refractive index change very similar to the one induced on the
active waveguide. The symmetrical injection of the current will reduce the carrier-induced
differential refractive index of the active waveguide and the intermixed passive waveguide to
almost zero while providing gain (for our wavelength-of-interest) only in the active waveguide.

In the following part, a QWI process for the InAlGaAs MQW is devised and
characterized by developing intermixed InAlGaAs MQW lasers and characterizing the lasing and
waveguiding properties of the lasers.
4.3. Quantum Well Intermixing of InAlGaAs MQWs

4.3.1. Introduction

For multiple quantum well (MQW) laser diodes operating at 1550 nm, InAlGaAs MQW has been known to have better temperature tolerance than the conventional InGaAsP MQW [36]–[39]. This due to the larger conduction-band offset of the InAlGaAs MQW ($\Delta E_c = 0.72\Delta E_g$) compared to the InGaAsP MQW ($\Delta E_c = 0.4\Delta E_g$) (fig. 4-15), which translates to increased electrons confinement over holes confinement in the wells. Since the electrons in the conduction-band have significantly higher mobility than the holes in the valance-band, the larger electrons confinement results in a considerable reduction in carrier leakage and Auger recombination. This makes active InAlGaAs MQW optical devices more efficient at room-temperature and hence InAlGaAs MQW should be more desirable for photonic integrated circuits (PICs).

\[
\Delta E_g = E_g(Barrier) - E_g(QW)
\]

Figure 4-15: Band diagram of a quantum well/barriers od InAlGaAs QW and InGaAsP QW.

Post-growth quantum well intermixing (QWI) is well established as a relatively simple and very efficient method for defining passive sections in semiconductor PICs [15], [40], [41]. QWI
techniques, such as impunity induced disordering, photo-absorption-induced disordering, and impurity-free vacancy-enhanced disordering (IFVD), enables the bandgap energy of the QWs to be adjusted by intermixing the atoms at the well/barrier interfaces. As a result, the sharp boundaries of the well become graded, the Eigen-energies of the electrons and holes are modified, and the bandgap energy of the quantum well is changed.

Among the various QWI techniques, IFVD has the advantages of limiting the lattice damage and free-carrier absorption and providing well-defined boundaries between intermixed and non-intermixed sections [15], [40], [41]. The IFVD process chosen in this work involves the deposition of dielectric capping films on top of a semiconductor MQW structure, followed by rapid thermal annealing at elevated temperatures. The thermal annealing initially creates point defects at the semiconductor-dielectric interface and then causes these point defects to diffuse through the entire semiconductor structure and ending in the substrate. Depending on several factors such as the film porosity, the atomic composition at the dielectric interface, and the density and type of native defects in the semiconductor, (vacancies and/or interstitials), the degree of intermixing of

Figure 4-16: the quantum well intermixing process.
the MQWs can vary greatly [15], [42], [43]. In fact, different films can be used either to promote the QWI process or to block it from happening.

For InAlGaAs MQW systems, a plasma-enhanced chemical vapor deposition (PECVD) of silicon nitride (SiNₓ) capping film is found to promote the IFVD process while a silicon oxide (SiO₂) capping film inhibits the MQW disordering [37], [42]–[44]. Unfortunately, the process usually leads to an increased waveguide loss for the intermixed QWs [37], [44]. In one report, the increase in the optical loss was attributed to Zn diffusing into the active region [44]. This can limit the use of IFVD for PICs application. In this paper, laser diodes with various degrees of intermixed InAlGaAs MQW are demonstrated, and the additional optical loss caused by the intermixing process is reported.

4.3.2. Devices Structure and Fabrication

The InAlGaAs MQW laser structure was grown on a Si-doped InP wafer using metal organic chemical vapor deposition (MOCVD) by a commercial semiconductor foundry. A graded index-separate confinement heterostructure (GRIN-SCH) was used to embed the InAlGaAs MQW active region (fig. 4-17). The wells were each 6 nm thick, and the barriers were each 9 nm thick. A 1.5 μm-thick Zn-doped InP layer was used as an upper waveguide cladding with a top 150 nm-thick Zn-doped InGaAs that was used as the electrical contact layer. A thin (15 nm) InGaAsP layer was grown in-between the upper InP layer at 50 nm above the active InAlAs confinement layer, to act as an etch-stop during the fabrication process (fig. 4-17). To characterize the IFVD of the InAlGaAs MQWs, several samples were prepared and intermixed to varying degrees. The first four samples were all capped with an 80 nm-thick layer of SiNx followed by a 200 nm-thick layer of SiO2 using PECVD. The samples were each annealed
separately for 20 seconds at 730°C, 750°C, 770°C, 810°C, and 830°C respectively in a nitrogen environment using the rapid thermal annealer (RTA). On a fifth sample, an 80 nm-thick layer of SiNx film was first deposited on the bare surface of the sample. Then, using contact-mask lithography and reactive-ion etching (RIE), the film was removed from half of the sample area. A 200nm-thick layer of SiO2 film was then grown over the entire sample, effectively creating two sections in the sample. The two-section sample was annealed in the RTA at 770°C for 20 seconds. Finally, the capping layers were removed from all the sample using buffered oxide etch (BOE) to dissolve the SiO2 film and using RIE to take out the SiNx film.

![Schematics of the InAlGaAs MQW bandgap diagram grown using MOCVD.](image)

Figure 4-17: Schematics of the InAlGaAs MQW bandgap diagram grown using MOCVD.

Fabry-Perot ridge-waveguides lasers were fabricated from the intermixed InAlGaAs MQW samples. The laser fabrication was started by the deposition of a 200 nm thick SiO2 film as a masking layer. Using positive photoresist and contact-mask lithography, 2-µm wide
waveguide stripes were patterned on the film. The SiO$_2$ film and the cladding layers were etched using RIE and wet-etching, respectively to realize ridge waveguides. To provide electrical isolation for the sides of the exposed ridges and planarization, Benzocyclobutene (BCB) was spin-coated to a thickness of 2.8 µm, and cured at 250°C for 2 hrs in a flowing nitrogen atmosphere. The surface layer of the BCB was then etched using the RIE until about 200 nm to 300 nm of the top of the waveguide ridges were exposed. The remaining SiO$_2$ was removed using BOE, and the p-type metal contact consisting of 7 nm of titanium and 350 nm of gold, was defined by photolithography and thermal evaporation in a vacuum chamber, followed by lift-off. The substrates of the devices were lapped and polished to a final thickness of about 125 µm, and the substrate n-contact consisting of 7 nm of nickel, 20 nm of germanium, and 200 nm of was evaporated on the sample and annealed at 400°C for 1 min. Finally, the four single-section devices with MQW that were intermixed to varying degrees using SiN$_x$ capping films annealed at different temperatures, were cleaved into laser chips each about 900 µm long. Additionally, the MQW sample that was covered on the one half with SiN$_x$ and the other half with SiO$_2$ and annealed at 770°C, was also cleaved to a length of about 900 µm (fig. 4-18). Finally, laser chips fabricated on the as-grown MQW sample to serve as a reference, was also cleaved and mounted for testing.
Figure 4-18: Schematic of the InAlGaAs MQW laser diodes.

Figure 4-19: The wavelength shifts (and the lasing spectra) of the as-grown, intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers.
4.3.3. Intermixing Characteristics

In this section, we discuss the results of the IFVD of the InAlGaAs MQW. When the annealing temperature of the SiN$_x$ capped MQW samples was increased from 730°C to 830°C, the lasing wavelength of the devices changed from 1541 nm to 1402 nm as shown in figure 4-19. The maximum shift in lasing wavelength was 147 nm from the as-grown lasing wavelength of 1549 nm. For the sample that was annealed at 770°C, the MQW section that was capped by SiN$_x$ lased at a wavelength that was shifted by 89 nm from the as-grown laser wavelength, while the laser wavelength from the MQW section that was capped by SiO$_2$, was only shifted by 6 nm.

The SiN$_x$ and SiO$_2$ capping layers have opposite effects on the IFVD of InAlGaAs MQW compared to many other MQW structures. For AlGaAs/GaAs MQW, InGaAs/GaAs MQW, InGaAs/InP MQW and InGaAsP MQW systems, a SiO$_2$ cap during the rapid thermal annealing promote the intermixing process; while a SiN$_x$ cap inhibits the intermixing process. Conversely, for InAlGaAs MQW, a SiO$_2$ cap inhabits intermixing while a SiN$_x$ cap promotes the intermixing of the MQW (as observed in figure 4-19). This behavioral change is most likely due to a combination of the different chemical compositions at the semiconductor-dielectric interface, and the different chemical compositions in the MQWs.

The chemical composition at the semiconductor-dielectric interface greatly influences the density and types of the point defects generated during the thermal annealing. AlGaAs/GaAs MQW and InGaAs/GaAs MQW are usually embedded underneath semiconductor claddings layers that contain gallium, with GaAs as the top contact layer. When these MQW structures are capped with SiO$_2$ and annealed at high temperatures, Ga will tend to out-diffuse into the SiO$_2$ thereby creating predominantly group III vacancies at the semiconductor-dielectric interface [42]
The diffusion of the group III vacancies through the epitaxial layers during the rapid thermal annealing is the main intermixing factor for AlGaAs/GaAs MQWs and InGaAs/GaAs MQWs. This is because a change in the bandgap between the wells and the barriers is achieved through the variation of the concentration ($C$) of group III alloys (Al, Ga, and In). The concentrations of group V alloy (As) are identical in the wells and the barriers because AlGaAs/GaAs MQWs and InGaAs/GaAs MQWs have only a single group V alloy. In contrast to SiO$_2$, Ga has considerably low solubility in SiN$_x$. Thus, capping the AlGaAs MQW with SiN$_x$ limits the generation of point defects and limits the QWI as a result.

Similar to AlGaAs/GaAs MQW and InGaAs/GaAs MQW, InAlGaAs MQW has a single group V alloy (As), and the concentration variations of group III alloys are creating the distinct bandgap energies of the wells and the barriers. Therefore, group III interdiffusion, caused by the movement of group III vacancies, is the main intermixing mechanism for InAlGaAs MQW as well. However, since the cladding layers of InAlGaAs MQW are different from the cladding layers of AlGaAs/GaAs MQW and InGaAs/GaAs MQW, the mechanisms for generating group III vacancies are different.

InAlGaAs MQW, InGaAs/InP MQW, and InGaAsP MQW structures usually have InP as the cladding layers ending with a thin top InGaAs contact layer. According to several group V interstitial interdiffusion models [43], [45]–[48], capping these layers with SiO$_2$ film induces predominantly group V interstitials diffusion during the RTA. This is most likely due to the out-diffusion of group III atoms (Ga and In) into the SiO$_2$ layer, leaving a substantial number of group V atoms in none-equilibrium positions at the lattice. These group V interstitials diffuse into the semiconductor structure through kick-off process, causing group V atoms diffusion...
between the wells and the barriers. The out-diffusion of group III atoms into the SiO$_2$ also
generate a limited number of group III vacancies casing group III atoms interdiffusion between
the well and the barriers.
Table 4-1: Point defects and resulted in QW diffusion when several MQW structures are capped with SiO2 and SiNx during the RTA.

<table>
<thead>
<tr>
<th>Capping Film</th>
<th>SiO2</th>
<th>SiNx</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AlGaAs/GaAs QW and InGaAs/GaAs QW</strong></td>
<td>Contact layer</td>
<td>GaAs</td>
</tr>
<tr>
<td>Point defects</td>
<td>Group III vacancies</td>
<td>Limited defects</td>
</tr>
<tr>
<td>QW Diffusion</td>
<td>Group III atom diffusion</td>
<td>Limited diffusion</td>
</tr>
<tr>
<td><strong>InGaAs/InP QW and InGaAsP QW</strong></td>
<td>Contact layer</td>
<td>InGaAs</td>
</tr>
<tr>
<td>Point defects</td>
<td>Group V interstitials/ Limited Group III vacancies</td>
<td>Group III vacancies</td>
</tr>
<tr>
<td>QW Diffusion</td>
<td>Mainly group V atom diffusion</td>
<td>Limited intermixing effects $\Delta C_{group\ V}$ is low</td>
</tr>
<tr>
<td><strong>InAlGaAs QW</strong></td>
<td>Contact layer</td>
<td>InGaAs</td>
</tr>
<tr>
<td>Point defects</td>
<td>Group V interstitials/ Limited Group III vacancies</td>
<td>Group III vacancies</td>
</tr>
<tr>
<td>QW Diffusion</td>
<td>Limited intermixing effects $\Delta C_{As} = 0$</td>
<td>Group III atom diffusion</td>
</tr>
</tbody>
</table>

For the InGaAs/InP MQW and InGaAsP MQW, the well and the barriers have a lower contrast between the concentrations of group III atoms compared to the contrast between the concentrations of the group V atoms ($\Delta C_{group\ V} \gg \Delta C_{group\ III}$). Therefore, the intermixing take effect primarily by the exchanging of group V atoms [45]. It has been demonstrated that capping of the InP and InGaAs layers with SiO2 followed by RTA generate more diffusion of group V atoms than group III atoms from the QWs (i.e. $k = \frac{L_V}{L_{III}} > 1$, where $L_i = \sqrt{D_i t}$ is the
diffusion length of atom \(i\), \(D_i\) is the diffusion coefficient of atoms \(i\), and \(t\) is the annealing time) [47], [48]. As a result, a SiO\(_2\) cap is very effective for the intermixing of InGaAs/InP MQW and InGaAsP MQW. On the other hand, an InAlGaAs MQW structure, that has identical group V concentration in the wells and the barriers (\(\Delta C_{As} = 0\)), is mostly unaffected by the increased exchange rate of group V atoms. Furthermore, since a SiO\(_2\) cap limits the number of group III vacancies through the diffusion of oxygen atoms and the generation of group V interstitials, it effectively impedes the intrinsic thermal interdiffusion of group III atoms during RTA.

However, the Si\(_N_x\) capping of the InAlGaAs MQW structure followed by RTA induces out-diffusion of In into the Si\(_N_x\) layer due to film porosity and low bonding energy of In-As compared to Ga-As [42], [43]. The reduced In concentration at the semiconductor-dielectric interface generates group III vacancies at the lattice and diffuse deep into the semiconductor structure passing through the MQW and causing an interdiffusion of group III atoms [38], [42], [49]. The wells and barriers of the InAlGaAs MQW have relatively high concentration disparity of In and Ga. Thus, the interdiffusion of In and Ga (group III) effectively change the concentration profile of the QW and causes the bandgap energy to change as observed experimentally.

4.3.4. Lasing Characteristics

From the light output vs current (L-I) curves of the laser diodes (fig. 4-20), it is observed that the lasing threshold \((I_{th})\) increased from 25 mA to 45.5 mA while the slope efficiency \((\eta_s)\) decreased from 0.101 W/A to 0.068 W/A, as the annealing temperature was increased from 750°C to 830°C (fig. 4-21 and 4-22). Compared to the as-grown laser \((I_{th} = 27.8 \text{ mA} , \eta_s = \)
0.121 \frac{W}{A}), the laser with maximally intermixed MQW (\lambda=1401 nm) experiences a 44\% reduction in \eta_s and a 64\% increase in I_{th}. However, for the MQW annealed at 770°C, the threshold current for the lasers from the protected MQW was practically unchanged at 27 mA while it increased for the device from the intermixed MQW (I_{th} = 36 mA). The slope efficiencies for the lasers from both sections were reduced (0.08 W/A for the protected laser and 0.07 W/A for the intermixed laser) as a result of the thermal annealing. The reduction in the laser performances of the devices with increasing degree of MQW intermixing is attributed to the depredated QWs and the increased internal loss caused by the thermal processing. It can be noted that one of the devices annealed at 730°C deviated from the above trend and had much weaker slope efficiency owing to an imperfectly cleaved facet.

Figure 4-20: The L-I curve of the as-grown, intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers.
Figure 4-21: Threshold current of the intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers.

Figure 4-22: Slope efficiency of the intermixing-inhibited, intermixing-promoted InAlGaAs MQW lasers.
4.3.5. Loss Measurements

The internal loss of a waveguide can be obtained by measuring the visibility of the Fabry-Perot fringes formed by scanning the wavelength of the light transmitting through the waveguide [9]. Knowing that the transmission of a Fabry-Perot cavity is

\[
T = \frac{I_t}{I_i} = \frac{(1 - R)^2 e^{-aL}}{1 + R^2 e^{-2aL} - 2R \cos(2\beta)e^{-aL}}
\]

where \(I_i\) and \(I_t\) are the incident and transmitted intensity, respectively, \(R = \sqrt{R_1R_2}\), \(R_1\) and \(R_2\) are the reflectivity of each of the end reflectors, \(\alpha\) is the cavity’s internal loss, \(L\) is the cavity’s length, and \(\beta\) is the round-trip phase change of the light. From equation (1), periodic fringes can be observed when \(\beta\) is varied, and maximum and minimum transmissions are acquired when \(\beta\) are odd and even multiple of \(\pi/2\), respectively. Thus,

\[
T_{\text{max}} = \frac{(1 - R)^2 e^{-aL}}{(1 - R e^{-aL})^2}
\]

\[
T_{\text{min}} = \frac{(1 - R)^2 e^{-aL}}{(1 + R e^{-aL})^2}
\]

Using equations (2) and (3), the internal loss can be expressed as

\[
\alpha = \frac{1}{L} \ln \left( \frac{1}{\sqrt{V} - 1} \right)
\]

where the visibility

\[
V = \frac{T_{\text{max}}}{T_{\text{min}}}
\]
The Fabry-Perot fringes of the lasers are observed using the setup shown in figure 4-23. The output of a tunable laser (Agilent 81640A) is launched into each fabricated laser separately. The wavelength of the tunable laser is scanned from 1585 nm to 1595 nm while measuring the transmitted power. Since the spacing of the Fabry-Perot fringes ($\lambda_{FSR} = \frac{\lambda^2}{n_e L} \approx 0.4 nm$) is significantly larger than the specified linewidth of the tunable laser ($\Delta\lambda \sim 1 \text{ fm}$), the fringes are expected to be resolved properly. The peaks and valleys of the fringes are well defined (fig. 4-24), therefore equations (4) and (5) can be used to obtain the internal loss coefficient ($\alpha$). The internal loss measurements are repeated several times and averaged for each device. Figure 4-24 shows the internal loss coefficient of the intermixed waveguide laser devices at 1590 nm. The loss coefficient of the waveguides is observed to increase from 9.1 cm$^{-1}$ for the MQW annealed at 750°C to 23.4 cm$^{-1}$ for the sample annealed at 830°C. In comparison, the devices fabricated on the un-intermixed MQWs annealed with SiO$_2$ capping layer exhibit a loss coefficient of 7.2 cm$^{-1}$ while the adjacent waveguides in the intermixed MQW region capped by SiNx, exhibit a loss coefficient of 14.1 cm$^{-1}$. 

Figure 4-23: Schematic of the setup used to observe the Fabry-Perot fringes of the intermixed InAlGaAs MQW laser cavities.
Figure 4-24: (a) Detected Fabry-Perot fringes by wavelength scanning of the light launching a single intermixed InAlGaAs MQW laser, and (b) Loss coefficients of the intermixed InAlGaAs MQW laser found at 1590 nm

4.3.6. Conclusion

Varying degrees of intermixing of InAlGaAs MQW are demonstrated by capping the sample with SiN$_x$ film followed by rapid thermal annealing for 20 s at elevated temperatures. Laser diodes fabricated from the intermixed InAlGaAs MQW operated at individual wavelengths that span from 1400 nm to 1520 nm. The intermixed lasers showed a reduction of slope efficiency (up to 44%) and increased threshold currents (up to 64%) compared to an as-grown InAlGaAs laser diodes. These behaviors can be partially attributed to the measured additional internal loss of the intermixed lasers. When annealed at 770°C, the increased internal loss due to the MQW intermixing ($\Delta \alpha = \alpha_{\text{intermixed}} - \alpha_{\text{unintermixed}}$) was measured to be 7.7 cm$^{-1}$. For one of the samples, a section of the InAlGaAs MQW was capped with SiO$_2$ film during the rapid
thermal annealing. For the laser diode in that section, the laser emission was at 1540 nm; only 6 nm shifted from that of the as-grown sample.
4.4. Fabrication of the Chiral Supermode Converter

The design of the chiral supermode converter is shown in figure 4-3 and 4-10, where the length of the device $L = 1.5 \text{ cm}$, the width of the waveguides are $w_0 = 4 \mu m$, the separation between the waveguides is $w_s = 3 \mu m$, the modulation depth of the passive waveguide $\Delta w = 0.5 \mu m$, and the height InP ridge $h = 1.07 \mu m$. We used the commercially supplied InAlGaAs MQW wafer shown in table 3-1 and figure 4-17 to fabricate the converter. The fabrication process can be divided into four parts, which are patterning alignment marks for the different photolithography, QWI of the passive waveguide, constructing the ridge waveguide structure, and applying the isolation and the two metal contacts. The process needs several photolithography processes. The masks for each photolithography were designed using AutoCAD and supplied using commercial foundry.

Figure 4-25: The fabrication the alignment marks.
The alignment marks (fig. 4-25) were applied to a freshly cleaned and cleaved 2.3 cm by 0.5 cm InAlGaAs MQW sample by first growing a 80 nm SiN\textsubscript{x} film of the sample using plasma-enhanced chemical vapor deposition (PECVD). Contact-mask lithography was used to pattern the alignment marks on a 500nm positive photoresist film on the SiN\textsubscript{x} film. The marks were transferred to the SiN\textsubscript{x} film using reactive-ion etching (RIE). Next, the marks were patterned into the wafer by wet etching the top 150-nm-thick InGaAs layer.

Figure 4-26: The QWI process of the InAlGaAs MQW.
The QW intermixed regions on the sample were defined and intermixed. As we have shown in the previous section, SiN$_x$ film promotes the intermixing while SiO$_2$ film inhibits the intermixing process. The previously grown 80 nm SiN$_x$ film was used for the intermixing-promoted sections. The intermixing-inhibit sections were defined using positive photolithography (fig. 4-26) aligned to alignment marks. RIE is used to etch away the SiN$_x$ films in the intermixing-inhibit areas as shown in step 6 of figure 4-26. Figure 4-27 shows a microscopic image of the intermixing-promoted film on the sample. A 200 nm thick SiO$_2$ was grown then on the sample using PECVD. The sample was placed in the rapid thermal annealer (RTA) where it was annealed for 15 seconds at 770°C. The SiO$_2$ and SiN$_x$ were removed using RIE.

![Figure 4-27: A microscopic image of the intermixing-promoted film on the sample](image)
Next, the waveguiding ridge structure was created (fig. 4-29). A fresh 200 nm low-stress SiN\textsubscript{x} film was deposited on the sample using PECVD. This film is going to be used as a hard mask for the etching of the waveguides. Positive photoresist was spin-coated on the film and the contact mask aligner used to align a mask to the alignment marks and expose the photoresist with UV light. The mask contains several copies of the design of the waveguide coupler (fig. 4-3) separated by straight waveguides to be used as a baseline for our measurements. The developed photoresist had the design of the EP encircling waveguide coupler. The design was transferred to the SiN\textsubscript{x} film using RIE. Figure 4-28 shows few images of the patterned SiN\textsubscript{x} features. Since the etch depth of the ridge waveguide has to be $h = 1.07 \mu m$ for the coupling coefficient to be $\kappa = 8.537 \text{ cm}^{-1}$, inductively coupled plasma reactive-ion etcher (ICP-RIE) was used since its etch rate can be controlled precisely compared to wet etching. Using the SiN\textsubscript{x} features as a mask, the 150-nm-thick InGaAs, the 50-nm-thick InGaAsP film, and 1070±30 nm of the InP layer were etched using the ICP-RIE. Next, O\textsubscript{2} plasma ashing was used to remove the polymers deposited during the ICP-RIE and RIE was used to remove the SiN\textsubscript{x} mask.

Figure 4-28: Images of the patterned SiN\textsubscript{x} features.
Figure 4-29: The fabrication process of the waveguide structure.

The next step is to apply the metal contact to devices (fig. 4-30). Benzocyclobutene (BCB) was used to planarize the waveguides. The BCB was spin-coated and cured, submersing the whole structure. Next, top surface of the BCB was etched using RIE until the top surface of the waveguides are exposed. Negative photoresist and the lift-off process was used to define the shape of the p-contact, where each waveguide coupler had a separate metal contact. The top metal contact, consisting 8nm of Ti and 550nm of Au, was evaporated using a thermal evaporator. The substrate of the sample was lapped down to 180\(\mu m\) and polished. The bottom
metal contact, consisting of 7 nm of Ni, 20 nm of Ge, and 200 nm of Au, was evaporated. The facets of devices were cleaved, and the devices were mounted to a thermally controlled stage of testing and characterization. Figure 4-31 shows a schematic of the fabricated device. The Y-couplers shown at the figures were cleaved out before the testing and characterization.

Figure 4-30: The application of the BCB and the metal contact.
Figure 4-31: A schematic of the fabricated InAlGaAs MQW waveguide coupler with the top metal contact exposed from the far-right coupler and waveguide to show the underlying features.
4.5. **Waveguide’s Gain Characterization**

The devices with the cleaved facets were mounted on a water-cooled stage. The straight waveguides were used to characterize the gain’s spatial distribution of a single probe. As shown in figure 4-32, the output of the waveguide is collimated and collected by a power detector. First, the probe, biased by 500 mA, is placed at the edge of the waveguide near the output facet ($z_0$). The output power is recorded. The probe was, then, transitioned away from the facet while recording the output power. Figure 4-33 shows the normalized power as a function of the position of the probe. The recorded power also represents the intensity $I(z)$ as a function of the distance from a fixed probe. $I(z)$ has a full width at half maximum (FWHM) of about 1.9 mm. It is important to note that the profile of $I(z)$ does not represent the profile of the gain $g(z)$. Instead, it represents the amplified spontaneous emission, which depends on the spontaneous emission and the gain. In this section, we are interested in finding the gain profile induced by applying a single probe on the waveguide. Once the gain profile of a single probe is defined, multiple probes can be applied at different positions to create the desired gain profile.

![Figure 4-32: The experimental setup for characterizing the gain profile of a single waveguide.](image)
Figure 4-33: the normalized detected intensity as a function of the position of the probe. The $z=0$ point of the $z$-axis is located at the output facet of the waveguide.

Assuming perfect confinement, each photon generated in the waveguide by spontaneous emission $I_s(z')$ propagate in the $z$-direction in the waveguide. $z'$ is the generation position of the photon. As the photon propagates a distance of $\Delta z$ it experiences a gain of $e^{g(z)\Delta z}$. For a photon propagating from $z'$ to $z$, it will experience a gain of $\prod_{z''=z}^{z'} \exp(g(z'')\Delta z''). I(z)$ is the sum all the photon generated by spontaneous emission and amplified by the gain. Therefore, $I(z)$ can be described by:

$$I(z) = \int_{z}^{z_{\text{max}}} I_s(z') \prod_{z''=z}^{z'} \exp([g(z'') - \alpha] \Delta z'') \, dz'$$  \hspace{1cm} (4-21)

We assume that the gain has a normal distribution of $z$ as it is proportional to the carrier distribution. Thus,
\[ g(z) = g_{\text{max}} \exp \left( \frac{z^2}{b^2} \right) \] (4-22)

where \( g_{\text{max}} \) is the peak gain of the material and it can vary with the current biasing, \( \alpha \) is the absorption coefficient of the material, and \( \Delta z_{\text{FWHM}} = 2.3548 \, b \). \( \alpha \) was measured using the setup in figure 4-23 and found to be \( \alpha = 38.1 \, \text{cm}^{-1} \). Assuming that both \( g(z) \) and \( I(z) \) linearly depends on the carrier density, the spontaneous emission can be described by:

\[ I_{\text{sp}}(z) = n_{\text{sp}} g(z) \] (4-23)

where \( n_{\text{sp}} \) is the spontaneous emission factor [9], [50]. Since we are interested in the gain profile, using a normalized version of equations (4-21) and (4-22) is sufficient for a good estimate. Equation (4-21) was simulated by assuming an arbitrary value of \( g_{\text{max}} \) and \( b \). A good fit of the measurement results was found when \( g_{\text{max}} = 46 \, \text{cm}^{-1} \) and \( b = 1.3 \, \text{mm} \), as shown in figure 4-34. This suggests that the FWHM of the gain profile is \( \Delta z_{\text{FWHM}} = 3.0613 \, \text{mm} \). By knowing the gain profile induced by a single probe, any desired gain profile can be applied using multiple probes at different positions and with different current biasing.

In order to confirm the validity of our estimate of the gain profile, we estimated the lasing threshold of the 15 mm long waveguide using the gain profile and confirm threshold experimentally. For a laser, the lasing threshold is the point where the total gain exceeds the total loss in the waveguide. The loss in the waveguide includes the absorption and scattering loss (\( \alpha \)) and the transmission through the two facets. Using the effective index of the mode in the waveguide, the transmission was found to be 72.55\%. Therefore, the two facet loss is \( \alpha_{2f} = -0.4277 \, \text{cm}^{-1} \). Figure 4-35 shows the estimated gain profile of four probes spaced evenly and
each is biased by 500 mA. The average gain induced by the four probes is \( g_{av} = -1.542 \, cm^{-1} \), which is below the lasing threshold. Experimentally, we found that this setup is not sufficient for lasing as suggested by our estimate. However, when we increase the gain of our setup to \( g_{max} = 48 \, cm^{-1} \), the average gain crosses the lasing threshold \( (g_{av} = 0.066 \, cm^{-1}) \) as shown in figure 4-36. Assuming a linear relationship between the gain and the current, a gain of \( g_{max} = 48 \, cm^{-1} \) is equivalent to a 522 mA biasing current for each probe. In practical, the lasing threshold was found to be around 550 mA for each probe (fig 4-37). The small discrepancy between our estimate threshold and the experimental threshold is most likely due to the nonlinearity of the gain induced by the gain saturation.

![Image](image.png)

**Figure 4-34:** the estimated gain profile that provides a reasonable fit of measured output power.
Figure 4-35: The estimated gain profile of four probes spaced evenly, each one is biased with a peak gain of 46cm⁻¹. The average gain is less than 0.

Figure 4-36: The estimated gain profile of four probes spaced evenly, each one is biased with a peak gain of 48cm⁻¹. The average gain is more than 0.
Figure 4-37: the normalized lasing spectrum of a single 1.5 cm long InAlGaAs MQW waveguide biased by four 550mA probes.

The lasing results of the single waveguide confirm the validity of our estimate to a limited accuracy. However, the accuracy of this estimate is sufficient for the gain modulation required for waveguide coupler since the waveguide coupler’s design is very robust and tolerant.
4.6. Experimental Setup and Device Measurements

In this part, we experimentally demonstrate the encirclement around the EP using the waveguide coupler. The four probes were used to bias a waveguide coupler. The spacing between the probes and the biasing was adjusted individually to induce the gaussian-like gain profile shown in figure 4-38. The probes are placed at $z_1 = 3.2 \, mm$, $z_3 = 6.3 \, mm$, $z_3 = 8.7 \, mm$, $z_4 = 11.8 \, mm$ with the corresponding gain of $g_1 = g_2 = g_3 = g_4 = 41.4 \, cm^{-1}$. As we can observe in figure 4-38, the coupler experience loss for $z < 2.5 \, mm$ and $z > 12.5 \, mm$. It would have been more efficient to increase the number of probes to 6 or more to provide gain along the whole waveguide coupler. However, we are limited by the space for all the probes and the probe positioners.

Figure 4-38: the gaussian-like gain profile induced to the coupled waveguides using 4 probes.
The output form both facets of the waveguide coupler were collimated using 40x microscopic lenses and directed to IR cameras. As we described earlier, the output eigenstate depends on the encirclement direction around the EP. Referring to figure 4-3, the output of the left facet of the coupler will have the supermode $|2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$, and the output of the right facet will have a supermode $|1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$. The far-field of the two supermodes were simulated using Rsoft as shown in figure 4-29. To observe the far-field experimentally, the collimating lenses were moved away from the facets to transition the focus point of the lenses away from the facets and observe the far-field interference of the between the output of the two waveguides.

\[ |1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad \text{and} \quad |2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix} \]

![Simulation of the far-field of the $|1\rangle$ and $|2\rangle$ supermodes of the waveguide coupler.](image)

Figure 4-39: Simulation of the far-field of the $|1\rangle$ and $|2\rangle$ supermodes of the waveguide coupler.
Figure 4-40: Captured far-field images of the coupled waveguide when the propagating wave experiences a CCW encirclement around the EP.

Output

$z = 0 \mu m$

$z = 10 \mu m$

$z = 20 \mu m$

$z = 30 \mu m$
Figure 4-41: Captured far-field images of the coupled waveguide when the propagating wave experiences a CCW encirclement around the EP. The gain of the IR camera was amplified in the right images.
Figures 4-40 and 4-41 show the captured images of the output of the left, \( |2\rangle = \begin{bmatrix} 1 \\ -1 \end{bmatrix} \), facet at different defocusing distances of the lens \( z \). First, the lens positioned at a distance of a focal length away from the facet \( z = 0 \). Next, the lens was moved away from the facet by a distance \( z \). The dark area induced by the destructive interference between the output of the two waveguides are clear in the far-field images. The captured power start to get very dim at \( z = 40\mu m \); thus, the gain of the IR camera was increased to resolve the images in figure 4-41. The unbalanced intensity of the two waveguides is due to the high absorption on the active waveguide at \( z < 2.5 \text{ mm} \) and \( z > 12.5 \text{ mm} \). To balance the intensity, we need to use more probes.

Figure 4-42: a gaussian-like gain profile induced to the coupled waveguides a peak gain smaller the coupling coefficient.
To confirm our observation, the behavior of the waveguide coupler was compared to two different cases. In the first case, the same waveguide was used, but the peak gain was reduced to prevent the encirclement of the EP, as shown in figure 4-42. According to the simulation shown in figure 4-9 (a), in this case, we will not observe the asymmetric supermode conversion properties associated with the encirclement of the EP. The second case was a waveguide coupler without the modulation of the width of the passive waveguide. Figure 4-43 shows the far-field of all three cases, a waveguide coupler without the width modulation of the passive waveguide, a waveguide coupler with modulated width but low peak gain, and the same waveguide coupler but with high peak gain. We can see from figure 4-43 that the dark area of between the center of the peak intensity of the two waveguides appears at the far-field of only the waveguide coupler that provides the encirclement of the EP.
Next, the output the right facet was characterized. According to our simulation, the output of this facet should always be $|1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ as it represents a CW encirclement around the EP.

Figures 4-44 shows the captured images of the output of the left, $|1\rangle$, facet at different defocusing distances of the lens ($z$). It is clear from the images that at the far-field, the output of the two waveguides interferes constructively, showing a bright spot at the center of the far-field image. This interference pattern matches what simulated of the $|1\rangle = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ supermode in figure 4-39.
Figure 4-44: Captured far-field images of the coupled waveguide when the propagating wave experiences a CW encirclement around the EP.
4.7. **Conclusion**

In this chapter, a chiral supermode converter was designed by precise manipulating of the propagation parameter of a coupled semiconductor waveguide structure. The chiral behaviors are the consequences of the encirclement of the EP. The coupler was designed to provide either a CW or CCW encirclement around the EP for the waves propagating in coupler depending on the propagation direction. As a result, the final supermodes depends only on the propagation direction. The coupler was fabricated and characterized, and the chiral behavior was confirmed experimentally. This coupler can be developed to many direction-dependent applications, such as a photonic isolator and a photonic lantern.
107

LIST OF REFERENCES


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