Integrated Waveguide Devices for Mode-Locked Lasers

by

Patrick T. Callahan

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Electrical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2018

© Massachusetts Institute of Technology 2018. All rights reserved.

Author .................................................................

Department of Electrical Engineering and Computer Science

April 20, 2018

Certified by ..............................................................

Franz X. Kaertner

Professor

Thesis Supervisor

Certified by ..............................................................

Erich P. Ippen

Professor

Thesis Supervisor

Accepted by ..............................................................

Leslie Kolodziejski

Chairman, Department Committee on Graduate Theses
Integrated Waveguide Devices for Mode-Locked Lasers

by

Patrick T. Callahan

Submitted to the Department of Electrical Engineering and Computer Science on April 20, 2018, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering

Abstract

Mode-locked lasers can provide a stable source of optical pulses with intrinsically low timing jitter, and as such have a broad range of important applications, both as sources of low-noise microwave signals and as the key enabling technology for optical frequency combs. Integrating such laser systems onto a chip using silicon photonics will dramatically reduce size and cost, thus increasing the accessibility of this technology for widespread deployment. Mode-locked lasers can also serve as master oscillators within distributed timing synchronization systems. These systems require precise measurement and control of timing drift and jitter, which can be performed by balanced optical cross-correlation. Integrated implementations of these timing detectors using waveguides in nonlinear crystals will significantly increase efficiency and sensitivity, enabling higher performance for synchronization. In this thesis, I have developed an integrated mode-locked laser on a CMOS-compatible silicon photonics platform, as well as an integrated balanced optical cross-correlator for use in timing jitter performance monitoring and timing distribution systems.

Thesis Supervisor: Franz X. Kaertner
Title: Professor

Thesis Supervisor: Erich P. Ippen
Title: Professor
Acknowledgments

First, I would like to thank my thesis supervisors, Professor Franz Kaertner and Professor Erich Ippen. Professor Kaertner was the one who encouraged me to apply to MIT in the first place, and his guidance and perennial optimism have been indispensable to my growth as a researcher. It is also thanks to Professor Kaertner that I became involved in silicon photonics, an exciting field that is ever increasing in impact. Directing two research groups on opposite sides of the Atlantic, contributing to and involved in seemingly every area of optics under the sun, Professor Kaertner yet always manages to be accessible and approachable to his students, with timely and critical technical advice and ideas. At first I was intimidated to have an office one door down from such an intellectual luminary as Professor Ippen, but as I learned how welcoming and supportive a mentor he is, fear was quickly transformed into gratitude. A ready fount of deep insight both technical and personal, Professor Ippen’s door was always open, and I am deeply grateful for that fact. I am grateful, too, for the many times Professor Ippen has helped me to think and see clearly, patiently listening as I puzzled through a problem out loud and deftly steering me toward the solution. I also owe thanks to Professor Michael Watts, who spearheaded many silicon photonics programs at MIT; much of my research was performed in close collaboration with his research group. It has been a privilege to have access to a 300 mm wafer-scale photonics process and state-of-the-art fabrication capabilities, much of which was made possible by these programs. Professor Watts’ strategic acumen and fierce intuition about what is feasible taught me a great deal about efficient approaches to research, both on the level of individual design problems and on the more abstract level of which problems are worth trying to solve. In addition, having the opportunity to practice leadership within the DODOS program was a tremendous growth experience I’m not likely to forget.

I would like to thank all the members of the Optics and Quantum Electronics Group that I have had the pleasure to work with on various timing distribution projects: Amir Nejadmalayeri, Michael Peng, Ming Xin and Kemal Safak at DESY. A special thanks to Kemal for making my time in Germany so thoroughly enjoyable. Also K. Ravi and Peter Krogen, with whom I had the distinct pleasure of sharing an office during the early years. I would also like to thank all the members of the core DARPA DODOS team: Katia Shtyrkova, Nanxi Li, Salih Madgen, Alfonso Ruocco, Neetesh Singh, Diedrik Vermeulen, Ming Xin,
and Jelena Notaros. Many thanks in particular to Nanxi Li, and to Gary Riggott of the Microsystems Technology Laboratories, who spent countless hours in the clean room performing gain depositions on innumerable mode-locked laser chips for the DODOS program.

Many thanks as well to the many current and former members of the Photonics Microsystems Group that I worked with and who helped me over the years: Cheri Sorace-Agaskar, who patiently taught me much about photonic design, Jonathan Bradley, Michele Moresco, Ehsan Hosseini, Jie Sun, David Cole, Anna Baldycheva, Zhan Su, Purnawirman, Erman Timurdogan, Chris Poulton, Matt Byrd, and Manan Raval.

I would also like to thank my personal friends and family, who were a much-appreciated source of support and happiness. To my parents, thank you for always believing in me, for encouraging me to reach high and teaching me to work hard, for nourishing in me a robust curiosity and pursuit of diverse interests. To Katia, thank you for all the adventures and philosophical debates, for all the hours upon hours spent thinking out loud together, and for always being ready to deliver a kick in the pants when the need arose. Above all, thank you for being a steadfast and dear friend through many trials and tribulations. To Jisung, brother – there are no words to express my gratitude for our friendship. That which can be spoken is already known, that which is known is more than can be spoken. How blessed we have been to find our paths once again intertwined during this part of the journey. To my sister Michaela, thank you for all the Callahan Tuesdays, for all the shenanigans, for putting up with me all these years, and for always being someone I can count on. Finally, to Kelsey, light of my life, my beacon amid the storm and churn – I could not have made it without you by my side. Thank you for always being there to hold me up when I was low, for faithfully cheering me along in the final stretch, for bringing endless joy into my life, and most of all for being exactly who you are. Is tú mo ghrá go deo.
## Contents

1 Introduction 8

1.1 CMOS-Compatible Integrated Mode-Locked Lasers .......................... 8

1.1.1 CMOS-Compatible Photonics Technology Platform ....................... 9

1.1.2 Key Application: Optical Frequency Synthesizer ....................... 10

1.1.3 Key Application: Timing Distribution Systems ....................... 12

2 Gain Model: Rare-Earth-Doped Aluminum Oxide 14

2.1 Rate Equation Modeling .................................................. 15

2.2 Gain Coefficient for Guided Modes .................................... 17

2.3 Spectroscopic Parameters .................................................. 19

2.3.1 Absorption Cross-Sections ........................................... 20

2.3.2 Emission Cross-Sections ............................................. 21

2.3.3 Refractive Index and Material Dispersion .............................. 23

2.4 Transfer Function Model for Excited-State Lifetime ..................... 26

2.4.1 Thulium-Doped Al₂O₃ Lifetime Measurement .......................... 29

3 Broadband Dispersion-Compensating Gratings in Silicon Nitride Waveguides 31

3.1 Bragg Grating Theory ...................................................... 32

3.2 Preliminary Device Design ................................................ 35

3.2.1 Simulation of Grating Performance ................................... 37

3.2.2 Experimental Results .................................................. 39

3.3 Broadband Device Design ................................................ 41

3.3.1 Simulation of Grating Performance ................................... 42

3.3.2 Experimental Results .................................................. 46
4 Integrated Thulium-Doped MLL: Laser Cavity and Components

4.1 Overall Laser Architecture ............................................. 48
4.2 Nitride Edge Couplers and Waveguides .............................. 50
4.3 Gain Waveguide ........................................................... 51
  4.3.1 Bend Waveguide Design Constraints ............................... 54
  4.3.2 Dispersion of Gain Waveguide ..................................... 55
  4.3.3 Waveguide Loss Measurement .................................... 56
4.4 Trench Transition ......................................................... 59
  4.4.1 Component Design and Function .................................. 59
  4.4.2 Device Performance: Experimental Results ...................... 61
4.5 Gain Waveguide Transition .............................................. 62
  4.5.1 Component Design and Function .................................. 62
  4.5.2 Device Performance: Experimental Results ...................... 63
4.6 Compact Bend for Segmented Architecture .......................... 64
4.7 Pump-Signal Combiner .................................................... 66
  4.7.1 Component Design: 1600 nm Pumping ............................. 67
  4.7.2 Device Performance: Experimental Results ...................... 71
4.8 Dispersion-Compensating Grating .................................... 72
  4.8.1 Component Design: FN Gratings ................................... 72
  4.8.2 Component Design: Broadband BN Gratings ..................... 74
4.9 Nonlinear Interferometer ............................................... 76
  4.9.1 Component Design .................................................. 77
  4.9.2 Device Performance: Experimental Results ...................... 77
4.10 Dispersion Budget ....................................................... 79
4.11 Full Laser Cavity Characterization .................................. 82
  4.11.1 Pump Absorption Measurements .................................. 82
  4.11.2 CW Laser Simulations ............................................ 83
4.12 Mode-Locked Laser Results .......................................... 86
  4.12.1 Spiral Architecture: Initial Results ............................ 87
  4.12.2 Spiral Architecture: Photonic Trench Modification .......... 89
  4.12.3 Segmented Architecture: Extended-Cavity SBR ................ 90
  4.12.4 Segmented Architecture: NLI Mode-Locking ................. 92
## 5 Integrated Erbium-Doped MLL: Laser Cavity and Components

5.1 Overall Laser Architecture ........................................... 93
5.2 Nitride Edge Couplers and Waveguides ............................ 94
  5.2.1 Nitride Rings and Group-Index Measurement ................. 95
5.3 Pump-Signal Combiner .................................................. 98
  5.3.1 Component Design ................................................... 98
  5.3.2 Device Performance: Experimental Results ................... 101
5.4 Gain Waveguide ....................................................... 103
  5.4.1 Waveguide Loss Measurement .................................... 105
5.5 Other Laser Components .............................................. 106
  5.5.1 Transition Components and Euler Bend ....................... 106
  5.5.2 Nonlinear Interferometer and Gratings ....................... 107
5.6 Dispersion Budget ..................................................... 109
5.7 CW Laser Simulations ................................................ 110

## 6 Integrated Balanced Optical Cross-Correlator

6.1 Theory and Principle of Operation ................................ 112
  6.1.1 Second Harmonic Generation in Waveguides .................. 114
  6.1.2 Balanced Optical Cross-Correlator ............................. 116
6.2 Simulation of Waveguide Conversion Efficiency ................. 117
6.3 Experimental Results ................................................ 120
  6.3.1 Preliminary Waveguide Devices ................................. 120
  6.3.2 Second Harmonic Conversion Efficiency ....................... 120
  6.3.3 Fiber-Coupled Cross-Correlator Performance ................ 121
  6.3.4 Fully-Integrated BOC Module .................................... 124

## 7 Conclusion

...
Chapter 1

Introduction

1.1 CMOS-Compatible Integrated Mode-Locked Lasers

Photonic oscillators have many important applications in defense and communications systems. The ability to efficiently couple to low-loss fiber networks has significant advantages for communications links that require remotely located transmitters, such as radio-over-fiber, phased-array radar, long-baseline radio astronomy, and timing distribution systems. Mode-locked lasers (MLLs) are capable of delivering short optical pulses at highly precise intervals; direct photo-detection of such a pulse train yields a comb of microwave frequencies that can be used as a master oscillator in various communications links. Coupled with the fact that mode-locked lasers can be designed to exhibit extraordinarily low noise [1–3], these lasers are therefore a natural choice for high performance microwave photonic oscillators. In addition, the introduction of 1f-2f interferometry [4, 5] to detect the carrier-envelope offset frequency \( f_{\text{ceo}} \) enables control over the absolute frequency of the optical modes, such that an \( f_{\text{ceo}} \)-stabilized mode-locked laser can act as an absolute frequency reference. Such systems are enormously useful for applications in which the absolute frequency must be known, such as spectroscopy and optical frequency synthesis.

The current state of the art systems can occupy an area ranging from a shoebox-sized commercial package to a full optical table with complex and expensive isolation apparatus. An integrated system on a chip has the advantage of a smaller size, weight, and power footprint, as well as the increased ease of isolating such a system from environmental fluctuations. In particular, since silicon is the most widely used material in the electronics industry, a silicon-based photonics platform will benefit from the ability to co-integrate photonics and...
electronic CMOS circuitry. Thus the possibility arises for manufacturing a fully integrated MLL, with driving electronics and photonic waveguides all fabricated monolithically in the same process flow. Silicon photonics can also leverage the mature fabrication technology and infrastructure that has been built up over the past several decades, which can enable a significant reduction in the marginal cost of manufacturing a device. Integrated mode-locked lasers have previously been demonstrated using erbium-doped alumino-silicate glass deposited on a silica wafer and etched into ridge waveguides [6–8]. However, these systems were not designed with CMOS-compatibility in mind, and were fabricated on specialized wafers dedicated to the photonic circuits. The primary focus of this thesis work is the design and characterization of an integrated mode-locked laser on a CMOS-compatible silicon photonics platform.

1.1.1 CMOS-Compatible Photonics Technology Platform

The integrated mode-locked lasers were designed for fabrication within the CMOS-compatible silicon photonics platform at the Colleges of Nanoscale Science and Engineering (CNSE) at the SUNY Polytechnic Institute. The fabrication facility uses a 300-mm wafer-scale process with 193-nm immersion lithography to produce high-resolution waveguides. The platform consists of silicon dioxide cladding layers, three silicon nitride layers, a silicon layer with several different doping levels for active components, a partial-etch silicon layer for the formation of ridge waveguides, two metal layers and associated vias, and a germanium layer for high-speed detectors. A diagram of the full active photonics layer stack is shown in Figure 1-1. In addition, two trenches are etched through the top oxide: a dicing trench for dicing apart the individual chips on the wafer and to facilitate edge coupling to fiber, and a photonic trench that is used in the formation of the gain waveguide. The gain material is then deposited into the photonic trench as a back-end process; the deposition is performed at MIT after receiving the chips from the fabrication facility.

The silicon layer is 380 nm and the partial-etch ridge is 100 nm, in order to achieve the optimal dispersion profile for supercontinuum generation. The bottom nitride layer is 400 nm and the other nitride layers are 200 nm. The nitride layers are deposited using plasma-enhanced chemical-vapor deposition (PECVD), and are then subjected to chemical-mechanical polishing (CMP) in order to reduce surface roughness and an annealing process to reduce the absorption due to excess hydrogen in the material. The top and bottom oxide
layers are 4\,\mu m thick. The gain waveguide makes use of the silicon nitride layers to help guide the optical mode, however, the nitride layers are beneath the metals in the photonic stack, and as such must be buried under several microns of oxide. The gain material is deposited on top of the chip as a back-end process, therefore the photonic trench is introduced in order to bring the gain material closer to the nitride layers. To form the photonic trench, the top oxide is etched away using reactive-ion etching, with the second nitride layer (SN) acting as an etch stop. The SN layer in the trench region is then removed, and a 100-nm thick oxide layer is deposited in the trench, such that the total oxide thickness between the first nitride layer (FN) and the bottom of the trench is 200\,\text{nm}. The gain material will be described in a later chapter.

1.1.2 Key Application: Optical Frequency Synthesizer

One of the primary motivations for the development of the integrated mode-locked lasers was to serve as the master oscillator within an optical frequency synthesizer, the demonstration of which was the core goal of the DARPA DODOS program. A diagram of the technical approach pursued by our team is shown in Figure 1-2. Pulses from the output of the mode-locked laser are fed into a supercontinuum-generation component, in order to obtain an octave-spanning spectrum. Light from the low-frequency portion of the spectrum is then filtered out and sent to a second-harmonic generator, and the frequency-doubled output
Figure 1-2: Diagram of the system architecture for an optical frequency synthesizer developed for the DARPA DODOS program.

is then combined with the fundamental harmonic to generate an interference signal at the carrier-envelope offset frequency. Once $f_{\text{CEO}}$ has been detected, it can be controlled and set to a known frequency with a feedback loop, using the pump power as the control signal. A separate control loop feeding back onto a heater to adjust the cavity length can then provide control over the pulse repetition frequency, at which point the mode-locked laser modes will be known in absolute frequency space. Frequency synthesis is then performed by locking a tunable laser to one of the comb lines, and using a frequency shifter to generate any desired offset between adjacent comb frequencies.

A key innovation by our team was the development of frequency-doubling in silicon by using electric-field-induced second-harmonic generation [9]. By applying a large DC electric field, the third-order nonlinearity $\chi^{(3)}$ in silicon can be converted into an effective second-order nonlinearity $\chi^{(2)}$. The electric field is generated by applying a current to a P-I-N junction, and quasi-phase-matching of the second-harmonic can then be achieved by periodically applying P-I-N junctions along a long silicon waveguide. This device enables the frequency synthesizer to be designed entirely with CMOS-compatible materials, and without the significant engineering difficulties associated with integrating nonlinear crystals into large-scale fabrication facilities. However, the choice of silicon as the frequency-doubling material does immediately introduce a constraint on the system architecture – since the bandgap of silicon is approximately 1.11 eV (corresponding to 1120 nm), light propagation at shorter wavelengths is not practically feasible. This means that the fundamental harmonic
input to the SHG device should be at a wavelength of 2240 nm or longer. For the supercontinuum device, we use silicon waveguides whose dispersion has been carefully designed such that dispersive-wave generation occurs for the critical short-wavelength region of the spectrum. These devices have been shown to generate octave-spanning spectrum between approximately 1.2 \( \mu m \) and 2.4 \( \mu m \) when seeded with femtosecond pulses at 1900 nm [10]. In order to generate enough pulse energy to seed the supercontinuum device without suffering from two-photon absorption in silicon, we therefore chose to design the integrated mode-locked laser for operation at 1900 nm using thulium as the active material to provide gain.

1.1.3 Key Application: Timing Distribution Systems

In the frequency domain, an \( f_{\text{CEO}} \)-stabilized mode-locked laser can provide a comb of frequencies spaced at multiples of a fundamental repetition rate, which is very useful for optical and microwave frequency synthesis. In the time domain, this corresponds to a train of ultrashort pulses separated by precise time intervals, which is very useful for timing synchronization. For example, free-electron laser facilities (FELs) require many optical and microwave sub-systems to be tightly synchronized in order to produce short X-ray pulses for pump-probe measurements of molecular dynamics and other fundamental scientific experiments. FEL facilities often make use of particle accelerators in order to generate relativistic electron beams, and as such tend to be very large facilities that require synchronization over long distances. The low timing-jitter of mode-locked lasers makes them an attractive candidate for a master oscillator within a fiber-coupled timing distribution network. Such systems have been implemented at VUV FELs such as FLASH in Hamburg and FERMI in Trieste; these systems typically achieve stable synchronization and diagnostics with about 10-fs accuracy, corresponding to length stabilization on the order of 1 \( \mu m \) over a distance of about 1 km. Next-generation FELs such as the Linac Coherent Light Source II (LCLS-II) at Stanford and the European X-FEL in Hamburg are anticipated to deliver X-ray pulses at durations shorter than 10 fs, and as such will require timing synchronization at the sub-femtosecond level, corresponding to 100 nm length stabilization.

In order to satisfy such stringent synchronization requirements, the timing detector must be able to resolve very small time offsets between pulses, and be capable of returning an error signal large enough to lock a feedback loop. Current femtosecond timing distribu-
tion systems make use of type-II second-harmonic generation (SHG) in periodically-poled potassium titanyl phosphate (PPKTP) bulk crystals to perform an optical cross-correlation, which returns a signal proportional to the time overlap of two input pulses [11, 12]. More recently, the use of waveguides in PPKTP has led to dramatic improvements in SHG conversion efficiency [13, 14], and preliminary operation of a fiber-coupled device showed the promise of this approach [15]. The second focus of this work will be the development and characterization of a waveguide PPKTP device for use as a balanced optical cross-correlator to detect timing jitter for timing distribution systems.

Outline of this Thesis

The first several chapters of this work will be concerned with the design and simulation of integrated mode-locked lasers, and their constituent components. In Chapter 2, a full three-dimensional model of the gain for guided modes is described, with model parameters derived from experimental characterization of the doped alumina glass used as the gain material. In Chapter 3, the design and measurement of chirped gratings is presented, for use as intracavity dispersion compensation elements within the mode-locked laser devices. Next, in Chapter 4, an integrated mode-locked laser designed for operation at 1900 nm is developed, with the complete design and simulation of all the individual components, in two different laser architectures. Some experimental results of these devices are also discussed. A mode-locked laser design at 1550 nm based on a similar architecture and components is described in Chapter 5. The mode-locked lasers were all developed in close collaboration with K. Shtyrkova, this development effort entailed a considerable amount of work over many years. A detailed investigation of the mode-locking regimes and stability, modeling and simulation of the full mode-locked devices, and experimental characterization can be found in [16]. The design and characterization of an artificial saturable absorber which was used as the mode-locking element is also presented in [16]. This work focuses primarily on the interdependent design and characterization of all the integrated components (except for the artificial saturable absorber) and how they must fit together into a broader laser architecture, as well as gain/laser modeling. Finally, in Chapter 6, the theory, design, and performance of a timing detector based on balanced optical cross-correlation using waveguides in PPKTP is presented.
Chapter 2

Gain Model: Rare-Earth-Doped Aluminum Oxide

Rare-earth-doped glasses and crystals are among the most common gain materials used in lasers and amplifiers. In integrated optics applications, the ability to deposit an amorphous glass layer via physical vapor deposition provides a significant advantage over crystalline host materials, which require epitaxial growth methods [17]. Aluminum oxide (Al$_2$O$_3$) has been extensively studied as a host material for rare-earth ions and has a number of positive qualities, chief among them the ability to deposit at low temperatures compatible with CMOS electronics [18]. For our purposes, we will be concerned with two specific gain materials, erbium-doped aluminum oxide and thulium-doped aluminum oxide, for laser operation at 1550 nm and 1900 nm respectively. That being said, the mathematical treatment in this chapter is general, and can in principle be applied to a large variety of gain materials. Figure 2-1 shows the energy levels and transitions relevant to laser operation using trivalent thulium and erbium ions. We include energy-transfer processes in the diagram for completeness, which will have a more significant impact on laser performance as the concentration of active ions is increased to high levels. In particular, energy-transfer upconversion can have a detrimental effect on gain, depleting the excited-state laser level and inhibiting population inversion. The impact of these processes in erbium-doped aluminum oxide has been characterized in detail in [19]. In highly-doped thulium fiber lasers and channel waveguides, the cross-relaxation effect has been shown to help increase the slope efficiency above 70% [20,21]. However, for simplicity, in the model described in this chapter these effects are assumed to be small and are not included in the equations. This chapter will focus on the development of a full three-dimensional gain model for guided modes, incorporating whenever possible the experimentally measured material parameters.
2.1 Rate Equation Modeling

In order to optimize the gain within the laser cavity, it will be useful to review the rate equations for the two-level system (corresponding to in-band pumping of erbium at 1480 nm and of thulium at 1610 nm) as well as the three-level system (corresponding to pumping of erbium at 980 nm and of thulium at 790 nm). The constituent transitions and cross-sections for both systems are illustrated in Figure 2-2. Denoting the population density of the ground-state energy level by $N_0$ and that of the excited-state by $N_1$, the two-level system is described by:

$$
\frac{dN_0}{dt} = -\sigma_{a,p} \phi_p N_0 - \sigma_{a,s} \phi_s N_0 + \sigma_e \phi_a N_1 + \frac{N_1}{\tau_1} \quad (2.1a)
$$

$$
\frac{dN_1}{dt} = \sigma_{a,p} \phi_p N_0 + \sigma_{a,s} \phi_s N_0 - \sigma_e \phi_a N_1 - \frac{N_1}{\tau_1} \quad (2.1b)
$$
where the subscripts \( p \) and \( s \) refer to the pump and signal wavelengths, respectively, \( \sigma_{a,i} \) are the absorption cross-sections, \( \sigma_e \) is the emission cross-section, \( \phi_i \) are the photon fluxes and \( \tau_1 \) is the excited-state lifetime. Equations 2.1a and 2.1b are subject to the boundary condition \( N_0 + N_1 = N_t \), where \( N_t \) is the concentration of thulium atoms in the host material. In steady-state, the ground-state population density becomes:

\[
N_0 = \frac{(\tau_1 \sigma_e \phi_s + 1)N_t}{\tau_1 [\sigma_{a,p} \phi_p + (\sigma_{a,s} + \sigma_e) \phi_s] + 1} \tag{2.2}
\]

For the case of a three-level system, the rate equations are somewhat more complicated, but still allow for a closed-form analytical expression in steady-state. Denoting the population density in the pumping level as \( N_2 \), and the laser excited-state and ground-state levels as before, we have:

\[
\frac{dN_0}{dt} = -\sigma_{a,p} \phi_p N_0 - \sigma_{a,s} \phi_s N_0 + \sigma_e \phi_s N_1 + \frac{N_1}{\tau_1} \tag{2.3a}
\]
\[
\frac{dN_1}{dt} = \sigma_{a,s} \phi_s N_0 - \sigma_e \phi_s N_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_2} \tag{2.3b}
\]
\[
\frac{dN_2}{dt} = \sigma_{a,p} \phi_p N_0 - \frac{N_2}{\tau_2} \tag{2.3c}
\]

where \( \tau_2 \) is the lifetime of the pumping level, and \( \sigma_{a,p} \) now refers to the absorption cross-section between levels 0 and 2. This set of equations is subject to the boundary condition \( N_0 + N_1 + N_2 = N_t \). In steady-state, after some simplification, it can be shown that:

\[
N_0 = N_t \left[ \frac{\tau_1 (\sigma_{a,p} \phi_p + \sigma_{a,s} \phi_s)}{(1 + \tau_1 \sigma_e \phi_s)} + (1 + \tau_2 \sigma_{a,p} \phi_p) \right]^{-1} \tag{2.4a}
\]
\[
N_1 = N_t \left[ \frac{(1 + \tau_2 \sigma_{a,p} \phi_p)(1 + \tau_1 \sigma_e \phi_s)}{\tau_1 (\sigma_{a,p} \phi_p + \sigma_{a,s} \phi_s) + 1} \right]^{-1} \tag{2.4b}
\]

For a free-space beam propagating through the active material, the optical power as a function of propagation distance is then described by the Beer-Lambert law:

\[
P_s(z + \Delta z) = P_s(z) e^{-(\sigma_{a,s} N_0 - \sigma_e N_1 + \alpha_{b,s}) \Delta z} \tag{2.5a}
\]
\[
P_p(z + \Delta z) = P_p(z) e^{-(\sigma_{a,p} N_0 + \alpha_{b,p}) \Delta z} \tag{2.5b}
\]

where \( \alpha_{b,i} \) refer to the bulk material background losses. For propagation of an eigenmode in a waveguide, the analysis is more complicated and will be described in the next section.
2.2 Gain Coefficient for Guided Modes

For modes propagating in the z-direction, the fields have the form \( \vec{E}(x, y, z) = \vec{E}_t(x, y)e^{-j\beta z} \), where the subscript \( t \) denotes the transverse field distribution and \( \beta = \beta' - j\beta'' \) is the complex propagation constant. The modal gain coefficient is then defined as \( g_m = -2\beta'' \), for power gain. Starting from Poynting’s theorem, the expression for \( \beta'' \) in a waveguide with arbitrary cross-section can be shown to be given by [22, 23]:

\[
\beta'' = \frac{\omega}{4} \iint \epsilon''(x, y) |\vec{E}_t|^2 dxdy
- \frac{1}{2} \iint \text{Re} \left\{ (\vec{E}_t \times \vec{H}_t^*) \cdot \hat{z} \right\} dxdy
\]

(2.6)

where \( \epsilon''(x, y) \) is the imaginary component of the permittivity, which is responsible for providing gain. If we denote the complex refractive index as \( n = n' - jn'' \), then \( \epsilon'' = \epsilon_r'' \epsilon_0 = 2n'n'' \epsilon_0 \). Following [23], we can define the bulk gain coefficient, \( g_b \), according to the amplification factor experienced by a plane wave traveling through the bulk active material, similar to Eq. 2.5a:

\[
E(z + \Delta z) = E(z)e^{-j\omega_0(n'-jn'')\Delta z}
\]

(2.7a)

\[
|E(z + \Delta z)|^2 = |E(z)|^2e^{-2\omega_0n''\Delta z} = |E(z)|^2e^{g_b\Delta z}
\]

(2.7b)

therefore \( g_b = -2\omega_0n'' \). The bulk gain coefficient will be determined by the degree of population inversion of the active ions, which in a waveguide will be spatially dependent. Finally, using the fact that \( \omega = c\omega_0 \), and simplifying Eq. 2.6, we arrive at the expression for the modal gain:

\[
g_m = \frac{\epsilon_0cn_A}{4} \iint \alpha_b(x, y) |\vec{E}_t|^2 dxdy
- \iint \text{Re} \left\{ (\vec{E}_t \times \vec{H}_t^*) \cdot \hat{z} \right\} dxdy
\]

(2.8)

where \( n_A \) is the real part of the refractive index of the active material, and the integral in the numerator is taken over the active region of the waveguide (the passive materials are assumed to be lossless in this equation, such that \( \epsilon'' \) is zero outside the active region). This is nearly identical to the expression derived in [23], except that here we have retained the spatial dependence of the permittivity (and thus the bulk gain).

To calculate the gain as the mode propagates through the waveguide, we first solve for the mode profiles at both the pump and signal wavelengths, using a real-valued eigenmode.
solver. This amounts to treating the imaginary component of the refractive index as a small perturbation, as suggested in [22, 24]. From the mode fields, we calculate the energy flux in the z-direction, $\Phi(x, y)$, and normalize the distribution for unity power:

$$
\Phi(x, y) \equiv \frac{\text{Re} \left\{ (\vec{E}_t \times \vec{H}_t^* ) \cdot \hat{z} \right\}}{\int \int \text{Re} \left\{ (\vec{E}_t \times \vec{H}_t^* ) \cdot \hat{z} \right\} dx dy}
$$

(2.9)

For a particular input pump or signal power $P_0$, we can then simply multiply $\Phi$ by $P_0$ to obtain the correct units. The photon flux distributions for the pump and signal are equal to the energy flux divided by the photon energy:

$$
\phi_i(x, y) = P_0 \Phi_i(x, y)/(h\nu_i)
$$

(2.10)

where $h$ is Planck’s constant and $\nu_i$ are the pump and signal frequencies. We then solve the rate equations for the steady-state population densities, in each pixel. The bulk gain and absorption coefficients are then given by:

$$
g_{b,s}(x, y) = \sigma_e N_1(x, y) - \sigma_{a,s} N_0(x, y)
$$

(2.11a)

$$
g_{b,p}(x, y) = -\sigma_{a,p} N_0(x, y)
$$

(2.11b)

Finally, we substitute $g_{b,i}(x, y)$ into Eq. 2.8 to calculate the modal gain/absorption for the signal/pump, using the original mode fields. The input powers are then updated by a factor of $e^{g_{m,i} \Delta z}$, and fed back into the rate equations for the next iteration. In this way we can solve for the signal power at the end of some arbitrary length of gain waveguide, given some initial seed and pump power. By solving the rate equations in each pixel and at each propagation step, the model automatically includes the effects of pump loss and gain saturation, as well as the effect of a nonuniform population inversion fraction due to the shape of the pump and signal modes. This is effectively a three-dimensional model of the gain, which allows different waveguide geometries to be compared directly.

We can also use Eq. 2.6 to model the effects of material losses in the waveguide. The bulk material loss can be denoted by $\alpha_b$. In this case, the exponent in Eq. 2.7b becomes $(g_b - \alpha_b)$ and we have $n'' = -(g_b - \alpha_b)/2k_0$. Therefore the integral in the numerator of Eq. 2.6 can be evaluated as two separate integrals, one involving the gain or absorption due to
the active ions, shown in Eq. 2.8, and one solely involving the material losses. Denoting the modal background loss as $\alpha_m$, we have:

$$\alpha_m = \frac{\epsilon_0 c \iint n(x, y)\alpha_b(x, y) |\vec{E}_t|^2 dxdy}{\iint \text{Re} \left\{ \left( \vec{E}_t \times \vec{H}_t^* \right) \cdot \hat{z} \right\} dxdy}$$

(2.12)

We can then evaluate the integral separately in the regions of the constituent materials, each with corresponding $n_k$ and $\alpha_{b,k}$ (which are now constants), where the subscript $k$ denotes a particular material layer in the compound waveguide (e.g. nitride, Al$_2$O$_3$, or oxide). This can be represented as the familiar sum over confinement factors:

$$\alpha_m = \sum_k \alpha_{b,k} \Gamma_k$$

(2.13a)

where

$$\Gamma_k \equiv \frac{\epsilon_0 c n_k \iint_K |\vec{E}_t|^2 dxdy}{\iint \text{Re} \left\{ \left( \vec{E}_t \times \vec{H}_t^* \right) \cdot \hat{z} \right\} dxdy}$$

(2.13b)

where $K$ denotes the region of the $k$th material. This is a fully-vectorial confinement factor expression for the material loss.

### 2.3 Spectroscopic Parameters

The next step toward an accurate gain model is to measure the various spectroscopic parameters that feature in the rate equations: $\sigma_{a,i}$, $\sigma_e$, $\tau_1$, as well as the background losses $\alpha_{b,k}$ and the refractive index. In the case of the absorption cross-sections, this is relatively easy to achieve, for example using a straightforward cutback-type measurement. The propagation loss can be directly measured, and the cross-section can then be extracted by independently characterizing the concentration of active ions, with a Rutherford back-scattering technique. The emission cross-section can be calculated from the absorption cross-section, although the equations that relate the two often rely on assumptions that are not always valid for amorphous glasses. The emission cross-section can also be extracted directly from a measurement of the gain. Measurement of the excited-state lifetime is sometimes more challenging, and is described separately in a later section.
2.3.1 Absorption Cross-Sections

The doped Al\textsubscript{2}O\textsubscript{3} films are deposited using the reactive co-sputtering technique, in which the aluminum and rare-earth ions are sputtered onto the samples in a vacuum chamber with a controlled oxygen in-flow. The chamber is held between 550-590\degree C, which was found to be the optimum temperature range in terms of optical propagation losses in the film. The electrical power applied to the metal targets controls the rate at which the atoms are sputtered into the chamber. By holding the aluminum target power fixed and varying the power applied to the rare-earth target, the concentration of active ions in the film can be adjusted as desired. After the deposition, the films are characterized with a Metricon 2010/M prism-coupling measurement system. A piece of blank SiO\textsubscript{2} wafer is included in each film deposition, which can then be measured separately from the photonics chips. Light is coupled into the film through a prism, which is then scanned mechanically across the length of the sample, along the direction of propagation. The exponential decay of the return signal can then be extracted, which yields a measurement of the optical propagation loss. This can be thought of as sampling the absorption at a fixed value of \( x = x_0 \), as a function of \( z \). For slab modes in the doped films, the bulk gain/absorption parameter can then be approximated as a constant, treating \( N_0(x_0, y) \approx N_0(x_0) \approx N_t \) for small input signal powers. The measured loss parameter is then related to the absorption cross-section by:

\[
\alpha_{\text{meas}} = \Gamma (\sigma_a N_t + \alpha_b) \tag{2.14}
\]

where \( \Gamma \) is the confinement factor in the thin film, \( \alpha_b \) is the bulk material loss, and in general \( \Gamma, \sigma_a, \) and \( \alpha_b \) are all wavelength-dependent. The thickness and refractive index of the film can also be extracted from the prism-coupler measurement, and the confinement factor can then be calculated from simulation by solving for the modes in the slab. For typical film thicknesses (900-1200 nm for most films), the confinement factor is estimated to be approximately \( \Gamma = 0.85 \).

The background loss of the Al\textsubscript{2}O\textsubscript{3} film can be measured by depositing a passive film without the inclusion of active ions. For typical films \( \alpha_b \) is very low, on the order of 0.1 dB/cm. For active films, we can estimate the background loss by measuring the propagation losses far from the absorption peak of the active ions, at 633 nm. Since the material losses are likely dominated by Rayleigh scattering, and this decreases with increasing wavelength, this
loss measurement can then serve as an upper-bound on the loss at the wavelengths of interest. It is worth noting that although the bulk material loss of the Al₂O₃ film may be low, the waveguide background loss for the gain waveguides on the integrated photonic chips may be considerably higher, due to scattering at the interfaces between various waveguide layers and sidewall roughness at waveguide edges. The waveguide losses should therefore be independently measured in order to accurately model laser behavior. The absorption cross-section for the $^4I_{15/2} \rightarrow ^4I_{11/2}$ transition in Al₂O₃:Er³⁺ at 980 nm was measured in [19] to be $\sigma_a = 2.0 \times 10^{-21}$ cm². The absorption cross-sections in Al₂O₃:Tm³⁺ for the two pumping wavelengths were measured by E.S. Magden, the results are shown in Figure 2-3.

### 2.3.2 Emission Cross-Sections

The stimulated emission cross-section can be calculated from the absorption cross-section by use of the McCumber relation [25, 26]:

$$\sigma_e(\lambda) = \sigma_a(\lambda) \exp\left(\frac{\epsilon - hc/\lambda}{k_BT}\right)$$

(2.15)

where $T$ is the temperature, $k_B$ is the Boltzmann constant, and $\epsilon$ is an effective energy difference between the Stark manifolds. In general, calculating the value of $\epsilon$ requires knowledge of the exact Stark energy levels within the manifolds, which is difficult to obtain. An estimate of $\epsilon$ can be generated if the sub-levels are assumed to be equally spaced in energy [27], though the accuracy of these methods when applied to doped amorphous glasses remains disputed [28, 29].
Another method for calculating the emission cross-section is to measure the fluorescence spectrum under excitation by a pump laser. The spectral dependence of the emission cross-section is related to the fluorescence by a modified version of the Füchtbauer-Ladenburg equation [30]:

$$\sigma_e(\lambda) = \frac{\eta \lambda^5 I(\lambda)}{8\pi n^2 c \tau_{rad} \int \lambda I(\lambda)d\lambda} \quad (2.16)$$

where $\eta$ is the quantum efficiency of the transition (usually approximated as $\eta \approx 1$), $I(\lambda)$ is the measured fluorescence spectrum, $\tau_{rad}$ is the radiative lifetime, and $n$ is the refractive index of the active material. This method therefore requires a separate measurement of the radiative lifetime, which can be challenging to separate from the overall excited-state lifetime experimentally if non-radiative effects are significant. The emission cross-section of $\text{Al}_2\text{O}_3:\text{Tm}^{3+}$ is estimated in [31] using this method, resulting in a value of $\sigma_e \approx 2.5 \times 10^{-21}\text{cm}^2$ at 1900 nm. However, the excited-state lifetime reported in [31] is considerably longer than what we measure in our films (3.1 ms compared to 570 $\mu$s), so caution is warranted here. A combination of McCumber theory and measured fluorescence scaled by the Füchtbauer-Ladenburg equation was used in [19] to characterize the absorption and emission cross-sections for the $^4I_{15/2} \rightarrow ^4I_{13/2}$ transition in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$, the results are reproduced in Figure 2-4. In this work, we use the measured value for $\sigma_e$ given in [31] for $\text{Al}_2\text{O}_3:\text{Tm}^{3+}$, and that given in [19] for $\text{Al}_2\text{O}_3:\text{Er}^{3+}$.

![Graph](image.png)

Figure 2-4: Absorption and emission cross-sections as a function of wavelength for the $^4I_{15/2} \rightarrow ^4I_{13/2}$ transitions in erbium. Courtesy of J. Bradley [19].

The simplest method may be to measure the small-signal gain directly by pumping an
active waveguide and seeding with a laser at the wavelength of interest. If the concentration of active ions is known, as well as \( \sigma_{a,s} \), then the value of \( \sigma_e \) can be extracted from the exponential growth factor given in Eq. 2.5a. Using Eq. 2.2, the exponential gain factor for a two-level system in steady-state is equal to:

\[
g = \sigma_e N_1 - \sigma_{a,s} N_0 = \sigma_e N_t - \frac{(\sigma_e + \sigma_{a,s})(\tau_1 \sigma_e \phi_s + 1)N_t}{\tau_1 [\sigma_{a,p} \phi_p + (\sigma_e + \sigma_{a,s})\phi_s] + 1} \tag{2.17}
\]

In the limit of small-signal gain, where \( \phi_s \approx 0 \), this reduces to:

\[
g_0 = \frac{(\tau_1 \sigma_{a,p} \phi_p \sigma_e - \sigma_{a,s})N_t}{1 + \tau_1 \sigma_{a,p} \phi_p} \tag{2.18}
\]

If all the other parameters are already known from independent measurements, recording the small-signal gain as a function of pump power and fitting to Eq. 2.18 will then yield the stimulated emission cross-section.

### 2.3.3 Refractive Index and Material Dispersion

The refractive index of the constituent materials in the waveguide was measured using the Metricon 2010/M prism coupling system. Prism coupling measurements are capable of characterizing the thickness and refractive index of thin films independently of one another, provided that the film thickness is sufficient to support multiple slab modes. For very thin films one of the parameters must be assumed in order to calculate the other. To measure the refractive index of the PECVD nitride used in the photonic chips, we measured a blanket wafer sample from the fabrication facility, with a thickness of 500 nm. It should be noted that the nitride blanket wafer is not subject to the same thermal cycles as the patterned nitride waveguides, and the refractive index of PECVD nitride is known to be rather sensitive to the deposition temperature. Therefore the nitride data may not be indicative of the actual refractive index or dispersion characteristics of the waveguides used in the laser cavities, and should be considered as a rough approximation only. The oxide layer was not measured, as the characteristics of SiO\(_2\) glass are well known. For the purposes of modeling we use the refractive index values reported in [32]. The aluminum oxide films were characterized with a passive film with a thickness of 1.5 \( \mu \)m. The measured data is shown in Figure 2-5, with the associated fitting curves and resulting material dispersion. The data were fit to curves.
given by the Sellmeier formula:

\[ n^2(\lambda) = 1 + \sum_i \frac{A_i \lambda^2}{\lambda^2 - B_i} \]  

(2.19)

where \( \lambda \) is typically given in units of \( \mu m \). The formula is a result of the classical Drude-Lorentz harmonic oscillator model, in which the \( B_i \) coefficients represent (squared) resonant frequencies and the \( A_i \) coefficients represent oscillator strengths. Strictly speaking, all coefficients should therefore be positive in order to correspond to physical solutions, though fits with negative coefficients are sometimes reported in the literature. It is also worth noting that the Sellmeier equation is only valid in regions far from the resonant frequencies, so the \( B_i \) chosen for fitting should reflect this fact. The fitting was performed as a constrained least-squares optimization in MATLAB, with the requirement that the coefficients be positive.

Initial characterization of the Al\(_2\)O\(_3\) index used a single pole in the Sellmeier equation, which resulted in fits that were rather poor. As a result two fits were generated, one fitting to the entire data set (dotted line in Figure 2-5b), and one fitting only to the data between 1.3-1.6 \( \mu m \) (dashed line in Figure 2-5b), in order to better capture the wavelength slope of the data in that region. From the initial fits we determined two estimates for the gain waveguide dispersion, and relied on these estimates to formulate the laser cavity dispersion budget, which will be discussed in a later chapter. The reason a single pole fit was chosen was that the addition of further poles did not appear to improve the fit at first. However, it seems likely that the initial fits were the result of landing on a local minimum when the least-squares optimization was first performed. It has been shown that fitting to the Sellmeier formula is highly sensitive to the initial values chosen in an iterative least-squares fitting [33], and that the best results are usually achieved with a three pole fit in which at least one of the \( B_i \) coefficients is in the ultraviolet range and one is in the infrared range [34]. The physics underlying this empirical intuition is that the UV oscillator corresponds to the electronic bandgap of the material, while IR oscillators correspond to molecular vibrational modes. A range of values for the electronic bandgap of amorphous Al\(_2\)O\(_3\) have been reported in the literature, depending on the method of fabrication. For RF-sputtered thin films, an absorption peak was found near 200 nm in [35]. Mid-IR spectroscopy performed in [36] revealed an absorption peak near 12 \( \mu m \), which likely corresponds to one or more vibrational
Figure 2-5: Sellmeier fits for refractive index, group index, and group-velocity dispersion for silicon nitride (a,c,e) and aluminum oxide (b,d,f). Measured data is denoted with squares, three-pole Sellmeier fits are shown with solid lines. A single-pole fit for Al₂O₃ is shown with the dotted line, and an alternate single-pole fit excluding the short wavelength data is shown with the dashed line.
Table 2.1: Sellmeier coefficients for silicon nitride (fit SiN) and aluminum oxide (fits 1-3) thin films. For Al₂O₃, fit 1 is the single pole fit, fit 2 is the single pole fit excluding the short wavelength data, and fit 3 is the three-pole fit. The squared residuals are summed over the 1.3-1.6 \( \mu \)m region as well as over the entire measured data set.

<table>
<thead>
<tr>
<th>Fit</th>
<th>( A_1 )</th>
<th>( A_1 )</th>
<th>( B_1 )</th>
<th>( B_1 )</th>
<th>( A_3 )</th>
<th>( B_3 )</th>
<th>( \sum_{IR} r^2 )</th>
<th>( \sum_{all} r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN</td>
<td>2.11891</td>
<td>0.04372</td>
<td>0.01977</td>
<td>0.03697</td>
<td>0.62935</td>
<td>0.04344</td>
<td>4.1 ( \times 10^{-3} )</td>
<td>7.8 ( \times 10^{-5} )</td>
</tr>
<tr>
<td>1</td>
<td>1.70677</td>
<td>0.01921</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>9.8 ( \times 10^{-6} )</td>
<td>7.8 ( \times 10^{-4} )</td>
</tr>
<tr>
<td>2</td>
<td>1.6419</td>
<td>0.04081</td>
<td>0.02424</td>
<td>0.0</td>
<td>0.02424</td>
<td>0.0</td>
<td>8.1 ( \times 10^{-8} )</td>
<td>7.8 ( \times 10^{-4} )</td>
</tr>
<tr>
<td>3</td>
<td>1.71208</td>
<td>0.01196</td>
<td>0.02759</td>
<td>0.01163</td>
<td>1.75803</td>
<td>144.891</td>
<td>3.1 ( \times 10^{-7} )</td>
<td>7.8 ( \times 10^{-4} )</td>
</tr>
</tbody>
</table>

modes. We therefore use these oscillator wavelengths as initial values for the \( B_i \) coefficients in the iterative optimization. When this procedure was followed the resulting Sellmeier fit was considerably improved. The coefficients and residuals for the silicon nitride fit and the various Al₂O₃ fits are summarized in Table 2.1.

As the fits are extrapolated out to the 2-\( \mu \)m wavelength region of interest for thulium lasers, the impact of choosing the correct Sellmeier coefficients is seen to be significant. In particular, the material dispersion is highly sensitive to the Sellmeier coefficients: for the single-pole fits the dispersion is normal, while for the three-pole fit it is calculated to be anomalous. This has significant ramifications for the mode-locked laser design. The dispersion in the 1.5-\( \mu \)m region used for erbium lasers is also strongly dependent on the fitting parameters, even though different fits match the measured data very well in that wavelength range. In [37] it was found that the concentration of active ions in Al₂O₃:TM⁺ has a measurable impact on the refractive index, though from the Sellmeier fits reported there, the dispersion does not appear to be significantly altered for typical values of the concentration, so this effect can be safely neglected. The divergent predictions for the refractive index and dispersion would be immediately resolved with a measurement of the index at longer wavelengths, but unfortunately the available equipment was limited to measurements below 1.7\( \mu \)m. Future designs would greatly benefit from additional long-wavelength characterization of the Al₂O₃ films.

2.4 Transfer Function Model for Excited-State Lifetime

Next, we investigate the excited-state lifetime of thulium-doped Al₂O₃, which had not been reported in the literature at the beginning of this work. The excited-state lifetime of erbium-doped Al₂O₃ has been characterized in [19]. The most common method for measuring the
lifetime is to pump the gain material to excite the active ions, remove the pump excitation, and then directly measure the exponential decay of the spontaneous emission signal. The pumping can be achieved either with a CW laser that is chopped or modulated with a square wave [38], or else by using a short pulse from a mode-locked laser [39]. It should be noted that re-absorption at the signal wavelength can result in a non-exponential decay, which complicates the measurement. The direct time-domain method requires a very sensitive photo-detector to capture the time dependence of the weak emission output. In addition, the electrical response of the detector must be sufficiently fast so as to properly resolve the time-domain behavior without distorting the emission waveform due to its internal bandwidth limitations. It can be difficult to obtain a detector that has both the required sensitivity and response time in the wavelength region of interest.

Another method which proved more useful for our application is to pump the active medium with a sinusoidal modulation, which in effect modulates the population levels. Due to the finite decay time of the excited state, the oscillation in population levels will lag behind the driving modulation signal as the modulation frequency is increased [40]. As the modulation frequency is increased further, the population levels cannot respond fast enough, and the modulation will be attenuated. The system therefore acts like a low-pass filter, with the shape of the filter determined by the excited-state lifetime. The variation in population levels can be probed by a seed signal at the laser wavelength, which will then have a modulation imparted on it due to the varying ground-state absorption. In this section we will develop a model for the transfer function between these two signals in order to extract the lifetime. The transfer function model was developed in close collaboration with E.S. Magden, as were the thulium lifetime measurements discussed later in this section [41].

Starting from Eq. 2.1a for a two-level system, let the pump flux be written as $\phi_p = \varphi_p(1 + m(t))$, where $\varphi_p$ is a constant and $m(t)$ is the modulation function, a small sinusoidal perturbation. Then let $N_0 = n_{0,ss} + n_0(t)$, where $n_{0,ss}$ is the steady-state ground level population density when $\phi_p = \varphi_p$, and is therefore a constant; $n_0(t)$ represents the deviation from steady-state. Then Eq. 2.1a becomes:

$$\frac{dn}{dt} = N_t \left( \phi_s \sigma_e + \frac{1}{\tau_1} \right) - \left[ \phi_s (\sigma_{a,s} + \sigma_e) + \frac{1}{\tau_1} \right] (n_{0,ss} + n_0) - \varphi_p (1 + m) \sigma_{a,p} (n_{0,ss} + n_0) \quad (2.20a)$$

where

$$N_t \left( \phi_s \sigma_e + \frac{1}{\tau_1} \right) - \left[ \phi_s (\sigma_{a,s} + \sigma_e) + \frac{1}{\tau_1} \right] n_{0,ss} - \varphi_p \sigma_{a,p} n_{0,ss} = 0 \quad (2.20b)$$
since \( n_{0,ss} \) is the steady-state solution to Eq. 2.1a. Substituting Eq. 2.20b into Eq. 2.20a, this simplifies to:

\[
\frac{dn}{dt} + \left[ \phi_s(\sigma_{a,s} + \sigma_e) + \varphi_p\sigma_{a,p} + \frac{1}{\tau_1} \right] n_0 = -m\varphi_p\sigma_{a,p}n_{0,ss} - m\varphi_p\sigma_{a,p}n_0
\]  

(2.21)

We now make the approximation that since the modulation amplitude is small, the perturbation in population density will also be small, such that the product term \( m\varphi_p\sigma_{a,p}n_0 \) can be dropped. This allows us to treat the system as linear, such that the transfer function is mathematically well-defined. Next, we take the Laplace transform of Eq. 2.21, which gives:

\[
s\tilde{N} - n_0(t_0) + \frac{\tilde{N}}{\tau_{eff}} = -\sigma_{a,p}n_{0,ss}\varphi_p\tilde{M}
\]  

(2.22a)

where \( \frac{1}{\tau_{eff}} \equiv \left[ \phi_s(\sigma_{a,s} + \sigma_e) + \varphi_p\sigma_{a,p} + \frac{1}{\tau_1} \right] \)

(2.22b)

and where \( \tilde{N} \) and \( \tilde{M} \) are taken to be the Laplace transforms of \( n_0 \) and \( m \) respectively. If we take \( t_0 \) to be the time when the modulation is turned on, then the system is in steady-state at \( t_0 \), and therefore \( n_0(t_0) = 0 \). Finally, we arrive at the desired transfer function \( H(s) \):

\[
H(s) = \frac{\tilde{N}}{\tilde{M}} = \frac{-\sigma_{a,p}n_{0,ss}\tau_{eff}\varphi_p}{1 + s\tau_{eff}} = \frac{C}{\omega_c + s}
\]  

(2.23)

which is easily recognized as having the form of a single-pole low-pass filter, with a corner frequency of \( \omega_c = \tau_{eff}^{-1} \). In the limit where \( \phi_s \) is very small, Eq. 2.22b reduces to:

\[
\frac{1}{\tau_{eff}} = \omega_c = \varphi_p\sigma_{a,p} + \frac{1}{\tau_1}
\]  

(2.24)

and therefore the corner frequency is linearly dependent on the average pump power. In order to extract the lifetime, we can then measure the transfer function for several values of \( \varphi_p \) and fit the corner frequency to a line. This also gives us a second method for characterizing the absorption cross-section \( \sigma_{a,p} \), which will be the slope of the linear fit.

A final subtlety worth noting is that Eq. 2.23 in fact describes the transfer function between the modulation signal and the ground-state population density. However, the output that is measured is the modulation imparted on the seed signal due to the time-varying ground-state absorption. According to Eq. 2.5a, the output power will be exponentially dependent on \( n_0 \), in the form \( P_{out} = Ae^{-\gamma n_0} \). Using a Taylor-series expansion, we can write the
output seed power as: $P_{out} = A \left[ 1 - \gamma n_0 + O(n_0^2) \right]$. Since the magnitude of $n_0(t)$ is small, we can safely neglect the higher-order terms. Crucially, the phase of $n_0(t)$ is unchanged, thus the transfer function between the output seed power and the input modulation signal will be equal to that given in Eq. 2.23 multiplied by a scalar, and the expression for the corner frequency given in Eq. 2.24 is still correct.

### 2.4.1 Thulium-Doped Al₂O₃ Lifetime Measurement

Using the framework described in the previous section, we set up an experiment to measure the excited-state lifetime of our thulium-doped waveguides. A schematic of the experimental setup is shown in Figure 2-6. The pump and seed lasers are passed through polarization controllers and combined in a WDM before being coupled into the device under test, in this case a chip with thulium-doped waveguides. The output is passed through an optical low-pass filter to block out the residual pump light, and is then collected onto a photodiode. The output of the photodiode is sent to a lock-in amplifier, which compares the output sinusoid to the input modulation signal and measures the amplitude and relative phase. By sweeping the modulation frequency, we can therefore characterize the transfer function. In addition to measuring the thulium-doped waveguides, we verified the technique by measuring a section of erbium-doped fiber, whose characteristics are well documented in the literature.

The results of both sets of measurements are shown in Figure 2-7. The input seed power was chosen to be 100 $\mu$W or less, in order to satisfy the approximation made in Eq. 2.24. After measuring the amplitude and phase response as a function of modulation frequency, we fit the resulting transfer function to a filter response, shown as solid lines in the figure. We then repeated the measurements for various input pump powers, and plotted the corner frequency for each measurement as a function of the pump power. The lifetime can then

![Figure 2-6: Schematic of the experimental setup to measure excited-state lifetime. Abbreviations are as follows: WDM – wavelength division multiplexer, DUT – device under test, LPF – low-pass filter, PD – photodiode.](image-url)
Figure 2-7: Transfer function measurements of (top) erbium-doped fiber and (bottom) thulium-doped waveguides. (a,d) Amplitude and (b,e) phase response as a function of modulation frequency for various input pump powers. (c,f) Frequency of the first pole as a function of pump power.

be extracted from the y-intercept of a linear fit, following Eq. 2.24. For the erbium-doped fiber, we used a pump wavelength of 980 nm because it was easier to filter out any residual pump light from the output. Although this pumping scheme is in fact a three-level system, the lifetime of the pumping level is significantly shorter than the excited-state lifetime, and therefore the system will still be well approximated as a single-pole filter.

As can be seen from the figure, the estimated lifetime of the erbium-doped fiber is 9.72 ms, which agrees well with values found reported in the literature [42]. For the thulium-doped Al₂O₃ waveguides, we used a pump wavelength of 790 nm, for similar reasons. However, in the case of thulium, the excited-state lifetime is shorter than that of erbium, so we anticipate that the filter response at higher modulation frequencies may be modified by the lifetime of the pumping level. Therefore for the thulium waveguides we used a two-pole filter to fit the transfer function, and used the position of the first pole to extract the laser excited-state lifetime. We find the lifetime to be approximately $(568 \pm 48) \mu$m, which is similar to that found in thulium-doped fibers [43, 44]. The slope of the linear fit yields an estimated value of the pump absorption cross-section of $\sigma_{a,p} = (5.83 \pm 0.40) \times 10^{-21}$ cm², which agrees well with the measured value at 790 nm reported in the previous section. With the lifetime characterized, we now have a complete set of spectroscopic parameters for the gain model.
Chapter 3

Broadband Dispersion-Compensating Gratings in Silicon Nitride Waveguides

The usefulness of chirped Bragg gratings for dispersion compensation is well-known, in part due to their widespread deployment in dispersion-managed fiber-optic systems [45–48]. One intuitive way to approach the subject is as follows: a Bragg mirror is formed by alternating layers of materials with different refractive indices, and each junction will induce a small reflection. For an incident wavelength $\lambda_0$, if the width of the layers is chosen such that $d_i = \lambda_0/4n_i$, then the reflections will constructively interfere and a large overall reflection can be obtained from the structure. A similar principle is at work in the case of a waveguide Bragg grating, though the analysis is somewhat more involved. Counter-propagating guided modes in a waveguide can be coupled together by means of a perturbation in the refractive index [49, 50], such that power carried by the forward-propagating waveguide mode will be progressively transferred into the backward-propagating mode, effectively reflecting the incoming power. For such a structure, ‘constructive interference’ or efficient power transfer will occur when the Bragg condition is satisfied:

$$\beta = \frac{\pi}{\Lambda}$$

(3.1)

where $\beta$ is the propagation constant of the guided mode and $\Lambda$ is the period of the perturbation. If the period is chirped, that is, smoothly varied as a function of propagation distance along the waveguide, then different wavelengths will satisfy the Bragg condition at different positions within the structure, and will therefore have different total propagation distances with respect to the entrance of the device. In other words, the group delay will be
wavelength-dependent, and therefore the structure can act as a lumped-element dispersion compensator.

A common problem that arises when using chirped gratings is the ripple in the group-delay response, which causes the sign of the dispersion to oscillate between positive and negative, and can severely limit their suitability as compensator devices. Theoretical studies of this effect in dielectric mirrors [51,52] have found that abruptly ‘switching on’ the grating causes a kind of impedance mismatch which introduces undesired phase distortions. The solution is to adiabatically turn on the coupling between forward and backward propagating modes, which is commonly referred to as apodization. In the next section we will summarize the theory used to design an apodized chirped Bragg grating using nitride waveguides.

### 3.1 Bragg Grating Theory

Of the various different mathematical methods that have been used to analyze waveguide gratings, the relative simplicity of coupled-mode theory most readily facilitates intuition, and is sufficiently accurate in most practical cases. The coupled-mode theory formulation of waveguide Bragg gratings has been studied extensively elsewhere [53], a brief summary is presented here. The grating is treated as a periodic perturbation to an otherwise z-invariant reference waveguide, as shown in Figure 3-1. Denoting the amplitudes of the forward and backward propagating modes as \( a_+(z) \) and \( a_-(z) \), respectively, the coupled-mode equations are given by:

\[
\frac{d}{dz}a_+ = -j\delta a_+ + \kappa a_- \\
\frac{d}{dz}a_- = j\delta a_- + \kappa^* a_+ \tag{3.2a,b}
\]

where \( \delta \) is the detuning parameter, or the deviation from the Bragg condition, \( \delta \equiv \beta - \pi/\Lambda \), and \( \kappa \) is the mode-coupling coefficient. If the z-averaged value of the permittivity modulation \( \Delta \varepsilon \) is zero, then the propagation constant \( \beta \) of the reference waveguide will remain unchanged by the introduction of the perturbation, which simplifies the analysis [54]. For the case of the corrugated waveguide shown in Figure 3-1, we therefore choose:

\[
n_{g}^2 = \frac{1}{2} \left( n_{\text{core}}^2 + n_{\text{clad}}^2 \right) \tag{3.3}
\]

For this choice of reference waveguide, the coupling coefficient between the forward and
backward propagating modes can be shown to be [53]:

\[
\kappa = \frac{(n^2_{\text{core}} - n^2_{\text{clad}}) \iint_{gr} \vec{E}^*_+ \cdot \vec{E}^- dx dy}{\lambda_0 \eta_0 \iint \text{Re} \left\{ \left( \vec{E}^*_+ \times \vec{H}^*_+ \right) \cdot \hat{z} \right\} dx dy}
\]

(3.4)

where \( \eta_0 \) is the impedance of free space, \( \vec{E}_\pm \) are the fields for the forward and backward propagating eigenmodes of the unperturbed waveguide, and the integral in the numerator is taken over the region of the index perturbation. This expression can be simplified by noting that the transverse electric fields for the forward and backward propagating modes are identical, and the longitudinal electric fields are opposite in sign. The integrand in the numerator is therefore \( \vec{E}^*_+ \cdot \vec{E}^- = |E_{x+}|^2 + |E_{y+}|^2 - |E_{z+}|^2 \). In many cases described in the literature a semi-vectorial approximation is then applied at this point, which is often sufficiently accurate for fiber modes, for example. However, in tightly-confined integrated waveguides this approximation is generally not appropriate, and here we have retained the fully-vectorial form for the coupling coefficient.

After solving the coupled-mode equations, the mode amplitudes after propagation through a uniform grating of length \( L \) can be summarized in matrix form:

\[
\begin{bmatrix}
  a_+(L) \\
  a_-(L)
\end{bmatrix} = \begin{bmatrix}
  T_{11} & T_{12} \\
  T_{21} & T_{22}
\end{bmatrix} \begin{bmatrix}
  a_+(0) \\
  a_-(0)
\end{bmatrix}
\]

(3.5a)
$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma L) - j\frac{\kappa}{\gamma}\sinh(\gamma L) & -j\frac{\kappa^*}{\gamma}\sinh(\gamma L) \\ j\frac{\kappa}{\gamma}\sinh(\gamma L) & \cosh(\gamma L) + j\frac{\kappa}{\gamma}\sinh(\gamma L) \end{bmatrix} \quad (3.5b)$$

where $\gamma \equiv \sqrt{\kappa^2 - \delta^2}$. The transmission and reflection coefficients of the grating can then be derived from the transfer matrix elements:

$$\begin{bmatrix} t \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 1 \\ r \end{bmatrix} \quad (3.6a)$$

$$t = T_{11} - \frac{T_{12}T_{21}}{T_{22}}, \quad r = -\frac{T_{21}}{T_{22}} \quad (3.6b)$$

The phase of the reflection coefficient will then determine the dispersion imparted by the grating, which can be cast as either a frequency or a wavelength derivative of the group delay $T_g$. To avoid confusion, in this thesis we will refer to the former as $D_{g,\omega}$ and the latter as $D_{g,\lambda}$:

$$\phi = \arg\left(-\frac{T_{21}}{T_{22}}\right) \quad (3.7a)$$

$$D_{g,\omega} = \frac{\partial^2 \phi}{\partial \omega^2} \quad (3.7b)$$

$$D_{g,\lambda} = \frac{\partial T_g}{\partial \lambda} = \frac{\partial}{\partial \lambda} \left[ \frac{\partial \phi}{\partial \omega} \right] \quad (3.7c)$$

The more useful mathematical form will depend on the application; for the purpose of calculating dispersion budgets and dispersion-induced pulse broadening the frequency derivative is often more useful, but in experiment it can sometimes be easier to obtain the group-delay as a function of wavelength. Anomalous dispersion obtains for $D_{g,\omega} < 0$ and $D_{g,\lambda} > 0$.

To model apodized chirped gratings, in which the coupling strength $\kappa$ and the grating period $\Lambda$ are changing as a function of $z$, we can simply treat the grating as uniform within one grating period, and concatenate the transfer matrices of each subsequent grating period in order to build up the transfer matrix of the complete device [55]. The design, simulation, and measured performance of two classes of waveguide Bragg grating devices will be described in the following sections.
3.2 Preliminary Device Design

There are several ways to introduce the periodic index modulation into a waveguide to form the grating. In fiber Bragg gratings the index modulation is written into the core by selective exposure to intense ultraviolet radiation, which results in a permanent increase in the refractive index due to the photosensitivity of the germanium-doped silica glass [56, 57]. For integrated silicon photonic circuits, the index change is often implemented by corrugating the sidewalls of a waveguide, such that the effective index of the mode is periodically modified [58, 59]. Since the index contrast between the core and the cladding in silicon waveguides is high, even a small modification of the size of the waveguide can result in an appreciable change in the effective index of the mode. This can be desirable for achieving a high reflectivity with a relatively small number of grating periods. The apodization can be implemented either by varying the depth or the duty cycle of the corrugation [60, 61].

Since the two-photon absorption effect in silicon precludes the use of that material within the mode-locked laser cavity, we form the grating in silicon nitride waveguides. Rather than corrugate the sidewalls of the waveguide, we implement the perturbation by introducing separate nitride pieces at the edges of the central waveguide, in a symmetric fashion [62]. Since the index modulation is still rectangular, the theoretical expressions summarized in the previous section are still correct, in particular the expression for the coupling coefficient $\kappa$ given in Equation 3.4 remains valid. The magnitude of $\kappa$ will be determined by the width of central waveguide and of the perturbation blocks, as well as the spacing between them. By varying the spacing, we therefore vary $\kappa$, which can be thought of as the strength of the grating. This method enables very small values of $\kappa$ to be realized, by increasing the spacing such that the mode overlap with the perturbation region is negligible. We therefore expect that the device will be able to achieve a smooth apodization profile, which will help to minimize unwanted ripples in the group delay.

The maximum achievable value of $\kappa$ will be constrained by the minimum separation between nitride pieces, set by the design rules of the fabrication facility to be 100 nm for the FN layer. The length of the perturbation blocks, and therefore the physical period of the grating, remained fixed in this design. The wavelength chirp was then achieved by tapering up the width of the central waveguide along the length of the structure, such that the effective index of the guided mode is linearly increased as a function of propagation...
Figure 3-2: Top-view mask layout of an apodized chirped grating, with nitride waveguides represented in green. The entrance to the grating is on the left, and the structure continues beyond the edge of the image.

Figure 3-3: (Left) Refractive index profile of the reference waveguide in the center of FN grating, with the nitride blocks taking on the averaged value $n_{gr}$ described previously. At this position in the grating, the width of the central waveguide is 890 nm, the width of the perturbation blocks is 1.2 μm, and the spacing is 610 nm. (Right) Resulting electric field amplitude profile at 1560 nm.

distance. This is effectively tuning $\beta$ instead of $\Lambda$ to implement the wavelength chirp. A schematic of the device is shown in Figure 3-2, and Figure 3-3 shows the optical mode for the unperturbed waveguide at a position in the center of the grating.

The preliminary device was designed before the inclusion of the BN layer to the photonics stack, so the grating was implemented in the FN layer. Since the FN layer is only 200 nm tall, the index contrast that can be induced by the nitride blocks is not very large. This in turn means that the peak value for the grating strength that can be achieved is not very high, and therefore many grating periods are necessary in order to build up sufficient reflectivity. This results in a rather long device, which means that the group-delay dispersion (GDD) will also be high. If a smaller GDD value is desired, the length of the grating must be reduced. If a high peak reflectivity is also to be maintained, this necessitates a smaller chirp of the grating period, in order to ensure that enough grating periods contribute to the reflection at the central wavelength. There is therefore a tradeoff for the FN devices between the minimum
achievable GDD and the bandwidth of the device. The FN gratings were originally designed by Purnawirman; the simulations and measurements of those devices, summarized in the following sections, were performed by the thesis author.

3.2.1 Simulation of Grating Performance

A linear chirp of the Bragg wavelength was implemented in all the FN devices, as mentioned previously, and several different apodization profiles were used. In the context of the mode-locked laser cavity, all the constituent components generally exhibit normal group-velocity dispersion; the gratings are therefore designed to provide net anomalous dispersion for the cavity in order to enable soliton mode-locking. Figure 3-4(a) shows the propagation constant of the unperturbed waveguide as a function of position along the length of the device, with the desired linear chirp. For the preliminary device designs, the grating strength $\kappa$ was varied according to a polynomial function, Figure 3-4(b) shows an example of a device with a quadratic profile. The simulated performance of three gratings with different target dispersion values, and therefore different grating lengths, is summarized in Figure 3-5. The devices shown here were designed to have a center wavelength of 1560 nm, and all use the quadratic apodization profile. According to simulation, each of these device designs results in a reflectivity of greater than 90% over a bandwidth of approximately 20 nm, with a roughly flat GDD profile over that wavelength band. The sidelobes in the reflectivity arise from the choice of apodization function, which does not ramp back down to zero at the end of the

![Figure 3-4](image_url)

Figure 3-4: Simulation of FN grating device with a linear chirp and quadratic apodization profile. (a) Propagation constant $\beta$ as a function of position $z$ along the length of the device. (b) Grating coupling strength $\kappa$ and corresponding gap between the central waveguide and perturbation blocks as a function of position.
Figure 3-5: Simulated performance of three FN grating devices with lengths 240 µm (blue), 360 µm (red), and 480 µm (green). (a,c) Reflectivity and group delay as a function of wavelength across the band of interest. (b,d) Reflection and group-delay dispersion in the usable portion of the grating spectrum.

Grating. There will therefore be an effective impedance mismatch at the end of the grating, and wavelengths which are reflected in this region of the device will experience oscillations in the group delay, which is indeed what is observed in simulation. Nevertheless, the GDD as a function of wavelength is broadly flat around the center wavelength, as desired.

One subtlety worth noting is that in principle the waveguides support both polarizations, and therefore the TE and TM modes will each have its own reflection band. Generally speaking the TE reflection will be stronger for these devices, since the geometry of the perturbation blocks is such that a higher mode overlap with the grating region is achieved for the horizontally-oriented mode. This is desirable, since the other components in the laser cavity are optimized for the TE polarization. However, care must be taken in the experimental setup to ensure that the correct polarization response is measured. For this waveguide geometry, the TE mode is the fundamental mode, so the TM mode will have a lower effective index for a given wavelength. The center wavelength that satisfies the
Bragg condition will therefore be shorter than for the TE mode, which is helpful in terms of discriminating the two reflection responses experimentally. The measurements of the FN grating devices are summarized in the next section.

3.2.2 Experimental Results

To measure the performance of the chirped grating devices, we used a LUNA OVA-5000 optical vector analyzer. The tunable laser output from the LUNA was passed through a polarization controller and coupled into the gratings using a cleaved SMF-28 fiber. Index-matching fluid was used at the chip facet to minimize spurious reflections. The coupling loss at the facet is estimated to be on the order of 2-3 dB per facet, for a total of 4-6 dB coupling loss on and off the chip. The LUNA instrument measures the full Jones matrix of an optical device, and as such returns the amplitude and phase of each Jones matrix element. It is therefore enables full characterization of the polarization-dependent response of optical components. To isolate the TE reflection response, we adjust the polarization controller at the input of the chip such that the measured Jones matrix is approximately diagonal. Compared to the principal TE and TM reflections, any cross-polarization terms are anticipated to be small, therefore we adjust the input polarization such that these matrix elements are minimized. Figure 3-6 shows the resulting amplitude and phase of the measured Jones matrix for one of the gratings. As can be seen from the amplitude response, the diagonal elements ‘A’ and ‘D’ (which correspond to the two principal polarizations) contain appreciable reflections, whereas the off-diagonal elements are negligible. The ‘D’ component amplitude is small, and increasing slightly at shorter wavelengths. Since we expect the

![Figure 3-6: Measured Jones matrix element amplitudes (left) and phases (right) for one of the FN gratings.](image)
center of the TM reflection band to occur at a shorter wavelength, as discussed previously, we therefore identify the ‘A’ component as the TE reflection.

Figure 3-7 shows the TE insertion loss, group delay, and GDD in reflection for gratings of three different lengths corresponding to the device designs simulated in the previous section. Most of the insertion loss observed in reflection mode is likely due to coupling loss, which is estimated to be between 4-5 dB. We can estimate the reflectivity by comparing the transmission and reflection measurements if the scattering losses are assumed to be small. Let $P_1$ and $P_2$ represent the measured power (in linear units) in the reflection mode and transmission mode, respectively. If the coupling losses for the two measurements are the same, then $P_1 = cR$ and $P_2 = cT$, where $c$ is the total coupling loss factor and $R$ and $T$ are the reflectivity and transmission of the gratings, which obey $R + T = 1$. Then we can estimate the reflectivity as $R = P_1/(P_1 + P_2)$. Figure 3-7(b) shows the result of this

![Figure 3-7: Measured performance of three FN grating devices with lengths 240 μm (blue), 360 μm (red), and 480 μm (green). (a) Insertion loss in reflection is shown in solid lines, transmission response is shown in dotted lines. (b) Calculated reflectivity assuming no scattering losses. (c) Group-delay and (d) group-delay dispersion as a function of wavelength.](image)
calculation, which can be considered an upper-bound (since $R + T < 1$ in the presence of scattering losses). As the length of the grating is decreased, the GDD decreases as expected, although the reflection bandwidth also decreases. The longest device is estimated to have a reflectivity of 99% between 1554 nm and 1566 nm. The mean GDD of that device was measured to be 0.125 ps/nm between 1554 nm and 1566 nm, with a standard deviation of 0.02 ps/nm across that wavelength range. The average measured GDD values at the center wavelength for each of the three devices are compared with the design targets in Table 3.1; as can be seen from the results the agreement between design and measurement is quite favorable. Importantly, this grating design does not suffer from significant group-delay oscillations within the wavelength range of interest, as can be seen from the plot.

<table>
<thead>
<tr>
<th>Device</th>
<th>Length</th>
<th>1dB BW</th>
<th>Target GDD</th>
<th>Measured GDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>s460</td>
<td>240 µm</td>
<td>17 nm</td>
<td>55 fs/nm</td>
<td>57 fs/nm</td>
</tr>
<tr>
<td>s690</td>
<td>360 µm</td>
<td>21 nm</td>
<td>87 fs/nm</td>
<td>99 fs/nm</td>
</tr>
<tr>
<td>s920</td>
<td>480 µm</td>
<td>26 nm</td>
<td>119 fs/nm</td>
<td>131 fs/nm</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of FN grating performance and comparison with design targets.

### 3.3 Broadband Device Design

The inclusion of the thicker BN nitride layer into the photonics stack enables a higher index contrast to be achieved within the same grating design paradigm. Compared to the FN gratings, a BN device of the same length should therefore be capable of achieving a broader reflection bandwidth. In addition, smaller GDD values should be achievable without sacrificing peak reflectivity within the wavelength band of interest. Several other changes to the design approach were implemented in order to improve device performance. For the broadband devices, the central waveguide remains fixed and we modify the Bragg wavelength by changing the length of the perturbation blocks. The chirp profile is determined by a polynomial function, the coefficients of which were optimized to generate a flat GDD profile across the wavelength band of interest. Contrary to the preliminary FN devices, we use an apodization function that is symmetric, following conventional wisdom from fiber Bragg grating design [63, 64]. Intuitively, the asymmetric apodization function will result in group-delay oscillations at the short wavelengths, since light at those wavelengths is reflected from the end of the structure, where there is an abrupt ‘shut-off’ of the grating strength. Indeed
this is what is observed both in simulation and measurement of those devices. Smoothly reducing \( \kappa \) back down to zero from its peak value should eliminate this behavior and may further increase the reflection bandwidth.

### 3.3.1 Simulation of Grating Performance

The \( m^{th} \) grating period was determined by a polynomial function, with \( m \) ranging from 1 to a maximum value of \( S \), which was adjusted along with the polynomial coefficients to achieve the desired GDD value:

\[
\Lambda_m = \Lambda_0 + A + Bm + Cm^2 + Dm^3
\]  

(3.8)

where \( \Lambda_0 \) is the period that satisfies the Bragg condition at the desired center wavelength, \( \Lambda_0 = \pi/\beta(\lambda_c) \). Since the application of the chirp tends to shift the center of the reflection band away from the desired \( \lambda_c \), the \( A \) coefficient can be thought of as a corrective parameter used to re-center the spectral profile. The higher-order coefficients are required in order to effect a constant GDD as a function of wavelength, chirping the period linearly will not yield the desired result. To get an intuitive sense of this, consider the detuning parameter \( \delta \), which is the deviation from the Bragg condition. When \( \delta = 0 \), the incident wavelength is phase-matched to the grating, and coupling to the back-propagating mode can begin to build up. Therefore the position in the grating at which the incident light begins to turn around is in large part determined by the \( \delta = 0 \) point, which in turn will be closely related to the group delay.

Consider the simulated behavior of gratings with two different chirping profiles summarized in Figure 3-8, one of which has a linear chirp \((B \neq 0, C = 0, D = 0)\) and the other making use of the higher-order coefficients. The apodization function for both cases examined here is identical. In the linear chirp case, when we plot \( \delta \) as a function of wavelength and position in the grating, we can see that the contour on which \( \delta = 0 \) is somewhat distorted, whereas for the other case it appears roughly linear. If we imagine the phase-matching point to indicate roughly where the light turns around, then a linear group-delay will be achieved when the \( \delta = 0 \) contour closely approximates a line. As can be seen from the simulated group-delay for these two examples, shown in Figure 3-8(d), this is achieved for the polynomial chirp but not for the linear chirp case. One contributing factor for this
is that group-velocity dispersion in the central waveguide (due to both material dispersion and waveguide dispersion) will result in \( \beta \) not being a linear function of wavelength, such that a linear chirp in \( \Lambda \) will not produce the desired linear group-delay. However, it has also been demonstrated analytically for dielectric mirrors that a linear chirp results in a positive third-order dispersion in general, regardless of group-velocity dispersion [52,65].

The parameters for four different BN grating designs, corresponding to different target GDD values, are summarized in Table 3.2. The choice of these coefficients resulted in roughly the same chirp profile for all the designs, Figure 3-9(a) shows the grating period \( \Lambda \) as a function of position in the grating for each device. Several different apodization functions were considered, including the Gaussian, raised-cosine, and sinc functions. Of these, the raised-cosine function was chosen because it resulted in the best overall device performance in simulation. Both the Gaussian and sinc functions exhibited larger ripples in

![Figure 3-8](image-url)

**Figure 3-8:** Comparison of polynomial and linear chirping profiles. (a) Detuning parameter \( \delta \) as a function of wavelength and position in the grating, for the linear chirp case and (b) for the polynomial chirp case. (c) \( \Lambda \) profile for the polynomial (blue) and linear (red) cases. (d) Simulated group-delay as a function of wavelength for the polynomial (blue) and linear (red) cases, with the desired linear function superimposed in black.
the GDD, although the sinc function did result in a broader reflection bandwidth. Further optimization of the apodization profile is possible, although the performance obtained from the raised-cosine function was sufficient for our purposes.

In order to include the impact of the discrete fabrication grid, the value of $\Lambda_m$ was rounded to the nearest grid point, which for our process is 1 nm. Therefore the chirp profile is not unrealistically smooth in simulation. Similar care was taken to simulate a realistic apodization function. First, we calculate $\kappa$ for several values of the gap between the central waveguide and the perturbation blocks. Then we interpolate the results, and store a look-up table of $\kappa$ values for every intermediate multiple of the grid resolution. To implement the apodization profile, then, we determine the desired value of $\kappa$ from the raised-cosine function, compare to the look-up table, and return the nearest stored value of $\kappa$ as well as the corresponding gap. The width of the central waveguide was 700 nm, and the width of the nitride blocks was 1.2 $\mu$m. For the BN layer, the minimum block separation set by the fabrication facility was 200 nm.

The simulation results for the four grating designs are summarized in Figure 3-10. As can

<table>
<thead>
<tr>
<th>$S$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$\kappa_{max}$</th>
<th>$D_{g,\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>$-2.8 \times 10^{-8}$</td>
<td>$2.0 \times 10^{-11}$</td>
<td>$1.9 \times 10^{-13}$</td>
<td>$-6.0 \times 10^{-17}$</td>
<td>$5.2 \times 10^{4}$</td>
<td>20 fs/nm</td>
</tr>
<tr>
<td>800</td>
<td>$-2.8 \times 10^{-8}$</td>
<td>$1.7 \times 10^{-11}$</td>
<td>$1.05 \times 10^{-13}$</td>
<td>$-2.5 \times 10^{-17}$</td>
<td>$5.2 \times 10^{4}$</td>
<td>26 fs/nm</td>
</tr>
<tr>
<td>1000</td>
<td>$-2.8 \times 10^{-8}$</td>
<td>$1.4 \times 10^{-11}$</td>
<td>$7.0 \times 10^{-14}$</td>
<td>$-1.8 \times 10^{-17}$</td>
<td>$5.0 \times 10^{4}$</td>
<td>33 fs/nm</td>
</tr>
<tr>
<td>1200</td>
<td>$-2.8 \times 10^{-8}$</td>
<td>$1.1 \times 10^{-11}$</td>
<td>$5.0 \times 10^{-14}$</td>
<td>$-1.0 \times 10^{-17}$</td>
<td>$4.8 \times 10^{4}$</td>
<td>38 fs/nm</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of parameters in BN grating designs

Figure 3-9: Chirp and apodization profiles for the BN grating designs. (a) Grating period as a function of position in each of the four BN devices. (b) Grating strength $\kappa$ and corresponding gap between the waveguide blocks as a function of position.
Figure 3-10: Simulated performance of four BN grating devices with lengths 300 μm (blue), 400 μm (red), 500 μm (green), and 500 μm (purple). (a,c) Reflectivity and group delay as a function of wavelength across the grating band of operation. (b,d) Reflection and group-delay dispersion in the usable portion of the grating spectrum.

It can be seen from the plots, these grating designs have significantly broader reflection bandwidths than the previous iterations. These devices were designed with a shorter laser cavity in mind, therefore the target GDD values are smaller. The shortest grating (about 300 μm length) is designed to have $D_{g,\lambda} = 20$ fs/nm, with > 80% reflection over a 60-nm bandwidth from 1530 nm to 1590 nm. The longest device (about 600 μm length) is designed for $D_{g,\lambda} = 38$ fs/nm, with at least 95% reflection over that same wavelength band. Compared to the previous designs, the BN devices are expected to have smaller ripples in the GDD spectrum. Further adjustments to the chirp and apodization functions may produce an even flatter GDD profile, using numerical optimization for example, although it is likely not necessary for our application, and the measured performance of the devices usually differs from simulation. The experimental results for the broadband gratings are summarized in the next section.
3.3.2 Experimental Results

The performance of the broadband gratings was measured with the LUNA optical vector analyzer. For these test structures, the nitride taper at the edge of the chip was designed to have a mode profile matched to that of a 3 μm-spot-size lensed fiber, rather than the cleaved SMF-28 fiber used previously. Otherwise, the experimental setup is the same as before, with the tunable laser output of the LUNA connected through a polarization controller to the lensed fiber, and index-matching fluid used between the fiber tip and the chip edge to minimize facet reflections. The transmission port of the grating was connected to an identical nitride taper on the opposite edge of the chip. The coupling loss at the facet is estimated to be 1.5-2 dB per taper, for a total of approximately 3-4 dB coupling on and off the chip. The results for the BN gratings (again, isolating the TE response) are summarized in Figure 3-11.

![Graphs](image)

Figure 3-11: Measured performance of the four BN grating designs, s600 (blue), s800 (red), s1000 (green), and s1200 (purple). (a) Insertion loss in reflection (solid lines) and transmission (dotted lines), including measurement coupling losses. (b) Magnified version showing the insertion losses in reflection. (c) Estimated reflectivity of each grating, assuming no scattering losses. (d) Measured group delay as a function of wavelength, with linear fits superimposed.
As can be seen from the data, the insertion loss in reflection for all four devices is approximately 3dB across the entire measurement range of the LUNA, this suggests that the reflectivity is close to 100% for each device. The variations in the insertion loss in reflection mode are largely within the precision of the measurement, therefore it is difficult to ascertain the reflectivity from this measurement alone. We use the same procedure as before to calculate the upper-bound on the reflectivity from the sum of the transmission and reflection measurements, the results are shown in Figure 3-11(c). The reflectivity for all devices is estimated to be > 80% across the measurement range of 1530 nm to 1600 nm, with the most highly reflecting device achieving > 90% across that entire band. The center wavelength for the reflection appears to be shifted to shorter wavelengths, although that may be an artifact of the calculation. We can reasonably expect scattering losses to be higher for shorter wavelengths, so the true reflectivity at those wavelengths is likely to be slightly less than the calculated upper bound.

The measured group delay as a function of wavelength is shown in Figure 3-11(d), with linear fits to the data superimposed. The slope of the fits yields an estimate of the GDD. A summary of the extracted GDD values for each device design across multiple chips is given in Table 3.3. The deviation with respect to the design target is generally quite small, less than 5% in most cases, although it is seen to increase for the longer devices. The fact that the error systematically increases as the device length is increased suggests that the parameters of the fabricated BN waveguides (width, height, or refractive index, for example) do not exactly match simulation, which is consistent with observed discrepancies in other BN devices measured on these wafers. However, the deviation from the target is relatively small and the performance of these devices is still perfectly suitable for the desired application.

<table>
<thead>
<tr>
<th>Device</th>
<th>Design</th>
<th>Chip 1</th>
<th>Chip 2</th>
<th>Chip 3</th>
<th>Chip 4</th>
<th>Mean Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>s600</td>
<td>0.020</td>
<td>0.0191</td>
<td>0.0189</td>
<td>0.0196</td>
<td>0.0198</td>
<td>3.25%</td>
</tr>
<tr>
<td>s800</td>
<td>0.026</td>
<td>0.0247</td>
<td>0.0244</td>
<td>0.0251</td>
<td>0.0254</td>
<td>4.23%</td>
</tr>
<tr>
<td>s1000</td>
<td>0.033</td>
<td>0.0308</td>
<td>0.0304</td>
<td>0.0314</td>
<td>0.0310</td>
<td>6.36%</td>
</tr>
<tr>
<td>s1200</td>
<td>0.038</td>
<td>0.0351</td>
<td>0.0353</td>
<td>0.0352</td>
<td>0.0351</td>
<td>7.43%</td>
</tr>
</tbody>
</table>

Table 3.3: Dispersion design targets and measured values for four different grating designs, across four different chips. GDD in units of ps/nm. Percent error with respect to target values are averaged across chips.
Chapter 4

Integrated Thulium-Doped MLL: Laser Cavity and Components

4.1 Overall Laser Architecture

Given that the size of the reticle is limited to 24x25 mm, a single straight gain waveguide will likely not be long enough to provide sufficient gain for the laser cavity. There are two options for increasing the gain length: either the gain waveguide must be bent, or else the optical mode must be coupled out of the gain region, bent in a different waveguide, and coupled back in to a subsequent straight gain section. In the first case, the cross-section of the gain waveguide remains unchanged as it is bent, and the resulting architecture resembles a spiral, shown in Figure 4-1. In the second case, the bend waveguide is optimized for compactness and requires various additional transition components. We refer to this as the segmented architecture, a schematic of this laser cavity is shown in Figure 4-2. The spiral architecture has the advantage of having fewer transition components in the cavity, but has the disadvantage of requiring a large bend radius and therefore occupying a large area on the chip. The segmented architecture has the advantage of allowing the bend waveguide to be optimized separately from the main gain waveguide, resulting in a much more compact structure, but requiring more transitions which potentially add loss to the cavity.

Apart from the bend waveguide, all the other constituent components of the laser cavity are common to both architectures. First, the pump light is coupled onto the chip with a tapered waveguide, then coupled into the cavity with the pump/signal combiner device. The pump and signal modes are coupled across the trench boundary using the trench transition, then coupled into the gain waveguide. After propagation through the gain section, a
nonlinear interferometer acts as an artificial saturable absorber to provide the mode-locking action, and also acts as one of the cavity reflectors. The laser output is coupled out of one port of this device and coupled off the chip. Finally, dispersion compensation for the cavity is achieved with a chirped Bragg grating that acts as the other reflector to form the laser cavity. The design and performance of each of these components will be discussed in detail in the following sections. In general the component designs are interdependent, and also depend on the choices made at the overall architecture level. A successful laser architecture must therefore take a holistic view of the overall laser cavity.
4.2 Nitride Edge Couplers and Waveguides

To couple light on and off the chip, we narrow down the width of the nitride waveguide in order to expand the optical mode into the cladding. The width of the waveguide at the chip facet is optimized such that the mode overlap with the input fiber is maximized. Given that the thickness of the top and bottom oxide layers is only 4 μm, the mode size at the facet should not be too large, otherwise light will be lost coupling into the silicon substrate. Therefore we choose to use lensed fibers to couple to the chip, and we design our edge couplers to match to a 3-μm mode-field diameter. We use both the FN and SN nitride layers, which we refer to as a double-nitride (DN) waveguide. For our target mode size, the DN edge couplers are expected to have slightly more efficient coupling than single-layer couplers due to the greater degree of symmetry of the resulting optical mode. After coupling onto the chip, the waveguide width is then slowly tapered up to confine the mode more tightly; this allows for compact bending and routing to the other photonic structures. The edge coupler width at the chip facet is 370 nm, the taper length is chosen to be 100 μm, and the routing waveguide width is chosen to be 1.5 μm, in order to have high confinement while maintaining single-mode operation.

To characterize the performance of the edge couplers, we first measure two taper test structures, with identical edge couplers on both sides of the chip, connected by different lengths of 1.5-μm-wide DN waveguide. The difference in throughput between the measurements gives us an estimation of the waveguide loss. Figure 4-3(a) shows the experimental

![Figure 4-3](image_url)

Figure 4-3: Edge-coupler characterization. (a) Waveguide loss calculated from cutback measurement of two test structures with different DN waveguide lengths. (b) Extracted coupling loss, after calibrating out DN waveguide losses.
results at 1900 nm, the loss is measured to be approximately 0.85 dB/cm. After subtracting out the calculated waveguide losses, we can estimate the coupling efficiency of the tapers and take the average of the two measurements, shown in Figure 4-3(b). The coupling loss is estimated to be 2.3 dB per taper at 1900 nm.

4.3 Gain Waveguide

As mentioned previously, the gain waveguide is formed by etching a trench into the top silicon dioxide layer, and then depositing a layer of thulium-doped Al₂O₃ on top. A thin layer of silicon nitride beneath the trench provides a guiding material for the optical mode, since the refractive index of Si₃N₄ is higher than the surrounding materials. A buffer layer of SiO₂ reduces the confinement factor in the nitride, and helps to push the mode up into the active material. A diagram of the layer stack is shown in Figure 4-4.

![Figure 4-4: Cross-sectional view of the gain waveguide layer stack. Step I: the layer stack prior to etching of the trench. Step II: the oxide is removed in the trench region using a reactive ion etch process, the second nitride layer serves as an etch stop and is also removed in the trench region. Step III: the active material is deposited on top of the chip and fills in the trench.]

The key design considerations for the waveguide cross-section are the modal gain and the ability to guide the pump and signal modes around the bend (for the spiral architecture). Ideally, we want to maximize the fraction of the signal mode that is confined in the active layer, and simultaneously minimize the mode area (so as to maximize the optical intensity), as this should result in the highest gain. However, we must also ensure that the pump mode adequately overlaps with the signal mode, or else the active ions in the region of the signal mode will not be efficiently pumped and the signal mode will experience excess absorption.

The design parameters are the thickness of the active film and the width of the nitride
layer beneath the trench. The cross-section of the gain waveguide is shown in Figure 4-5, along with the intensity distributions for the signal and pump modes. As can be seen from the figure, the nitride piece below the trench is segmented into several smaller pieces. This reduces the effective index of the nitride layer, and therefore helps to increase the fraction of the mode that is confined in the active material. The width and spacing of the small nitride pieces can be manipulated in order to increase the pump-signal mode overlap in the active region, but it should be noted that this does not necessarily result in higher gain. For smaller input pump powers, if the pump intensity distribution is too diffuse then the local intensity may not be enough to invert the population of active ions, resulting in absorption for that region of the waveguide. To illustrate this effect, Figure 4-6 compares these two metrics for three different waveguide design examples, corresponding to different degrees of confinement in the nitride layer. The pump-signal mode overlap is calculated as:

\[
O = \frac{\left| \iint_A E_{x,s}E_{x,p}^*dxdy \right|^2}{\iint |E_{x,s}|^2dxdy \iint |E_{x,p}|^2dxdy}
\]  

(4.1)

where the modes are approximated to be TE, therefore \( |\tilde{E}(x,y)|^2 \approx |E_x|^2 \), and the subscripts \( s, p \) refer to the signal and pump modes respectively. The subscript \( A \) denotes an integral taken over the active region of the waveguide. The small-signal gain coefficient is calculated using the gain model described in Chapter 2, solving the rate equations in each pixel of the computational domain. For this calculation the concentration of thulium atoms was chosen to be \( 3 \times 10^{20} \text{ cm}^{-3} \).

The solid curves in Figure 4-6 correspond to an arrangement of five nitride pieces, each
500 nm wide and spaced apart by 300 nm. This is the final configuration that was chosen for the laser cavity. The dashed curves correspond to five 600 nm wide pieces spaced by 200 nm each, such that the mode is more confined in the nitride. The dotted curves correspond to five 350 nm wide pieces spaced by 350 nm, to increase the fraction of the mode confined in the active layer. As can be seen from the figure, increasing the pump-signal mode overlap increases the gain in most, but not all cases.

![Figure 4-6: (Left) Pump-signal mode overlap for three waveguides with different nitride configurations. Solid curves correspond to the final selected cross-section, shown in Figure 4-5. (Right) Small-signal gain coefficient for the same waveguide designs, for 50 mW input pump power (blue), 100 mW (orange), 200 mW (green) and 400 mW (purple).](image)

The confinement factors in each material are summarized in Table 4.1 for the final gain waveguide design. Increasing the fraction of the modes that is confined in the active layer – whether by thinning the nitride pieces or by increasing the thickness of the thulium film – has the effect of reducing the lateral confinement of the mode. This can become a problem if the edges of the mode begin to interact with the sidewall of the trench region, thereby increasing scattering losses, and can also pose challenges for bending the waveguide in a compact way, as will be discussed in the next section.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Gamma$(1600nm)</th>
<th>$\Gamma$(1900nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>0.83</td>
<td>0.79</td>
</tr>
<tr>
<td>$\text{Si}_3\text{N}_4$</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\text{SiO}_2$</td>
<td>0.133</td>
<td>0.17</td>
</tr>
<tr>
<td>Air</td>
<td>0.007</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Table 4.1: Confinement factors in the constituent material layers of the gain waveguide.
4.3.1 Bend Waveguide Design Constraints

For the spiral architecture, we use the same waveguide cross-section for the straight sections and for the bends, in order to avoid additional transitions that add complexity and potentially loss to the cavity. In general, the mode in the bend waveguide is not exactly the same as in the straight section, therefore there will be some degree of mismatch at the entrance to the bend. This mismatch can be reduced by increasing the radius of the bend, although there are physical limits on the size of the bend dictated by the available space on the chip. Therefore, we need to take the bend loss into account when optimizing the waveguide cross-section.

Figure 4-7 shows the mode overlap as a function of the thickness of the thulium film. The mode coupling is calculated similarly to the pump-signal overlap integral given in Eq. 4.1. As the thickness is increased, the bend mode is increasingly distorted with respect to the straight waveguide, resulting in a decreased overlap. This effect is more significant at the

![Figure 4-7](image_url)

**Figure 4-7:** (Left) Mode overlap between the straight and bend waveguides for the fundamental pump and signal modes, for a bend radius of 3.5 mm. (Right) Magnified version.

![Figure 4-8](image_url)

**Figure 4-8:** Mode profiles at 1600 nm for the spiral bend waveguide at different film thicknesses: (a) 1.18 μm (b) 1.22 μm (c) 1.26 μm. The bend waveguide has a radius of 3.5 mm and a trench width of 70 μm, mode profiles were simulated in MATLAB.
pump wavelength; pump mode profiles for several film thicknesses are shown in Figure 4-8. For thicknesses greater than 1.2 μm, the pump mode will primarily be coupled to higher-order modes in the bend that are guided by the trench sidewall, and will therefore suffer increased scattering loss due to roughness at the sidewall. In addition, the coupling back into the straight waveguide upon exiting the bend will generally be reduced due to multimode interference. For the segmented architecture, we make use of a transition component to couple the light out of the active region and into a thick silicon nitride waveguide with a high degree of confinement, such that it can be bent with a much smaller radius and without being sensitive to the thickness of the thulium film.

4.3.2 Dispersion of Gain Waveguide

The dispersion of the waveguide will be strongly influenced by the material dispersion of the Al₂O₃ film, considering that a large fraction of the mode is confined in that layer. Depending on which Sellmeier fit we choose among those described in Chapter 2, the estimate for the waveguide dispersion may be quite different. Figure 4-9(a) shows the simulated group-velocity dispersion for the gain waveguide for each of the different Al₂O₃ Sellmeier fits previously summarized in Table 2.1. The results vary dramatically depending on which fit is chosen, with the two single-pole Sellmeier fits yielding normal dispersion, and the three-pole fit giving anomalous dispersion. Prudence dictates that in the face of such uncertainty regarding the true value, we design the cavity such that the worst-case dispersion will still be manageable within the overall dispersion budget.

![Figure 4-9: Simulated group-velocity dispersion of the gain waveguide in fs²/mm, for the three different Al₂O₃ Sellmeier fits. Dotted, dashed, and solid curves correspond to ‘Fit 1’, ‘Fit 2’, and ‘Fit 3’ in Table 2.1, respectively. (a) Dispersion as a function of wavelength for a film thickness of 1.1 μm. (b) Dispersion at 1900 nm as a function of Al₂O₃ film thickness.](image-url)
Figure 4-9(b) shows the dispersion at 1900 nm as a function of the film thickness, which is seen to decrease as the film thickness is increased. Given that the gain waveguide is several centimeters long, its GDD will contribute a significant fraction of the net dispersion in the laser cavity. In general a smaller (more anomalous) GDD is therefore preferable, in order to ease the requirements placed on the chirped grating for compensation. For the spiral architecture, we choose a thickness of 1.1 µm for the Al₂O₃ film, which represents a compromise between modal gain, waveguide dispersion, and bend losses. For the segmented architecture, the bend waveguide is largely unaffected by the film thickness, although the performance of the transition components into and out of the bend will be dependent on the thickness to some extent.

4.3.3 Waveguide Loss Measurement

The fact that the gain waveguide is weakly guided presents challenges for designing a waveguide loss test structure. With the reticle length limited to 2.4 cm, a straightforward cutback measurement will likely not yield enough loss to accurately differentiate between cutback rows. Paperclip and ring-type structures rely on bends that would need to be impractically large for this waveguide. However, with an independent measurement of the coupling losses, we can at least obtain an estimate of the waveguide loss by measuring a straight section with a known length. The coupling loss of the double-nitride tapers was measured to be approximately 2.3 dB, as shown in Figure 4-3(b). A 1.1-µm-thick passive Al₂O₃ film was deposited on the gain waveguide test structure, and the transmission was then measured. Light is coupled on-chip through the taper, then passed through the various transition components into the gain waveguide, and back out again on the other side of the structure. The transition components contribute a negligible amount of loss, as will be discussed in later sections.

The measured transmission of the test structure is shown in Figure 4-10(a), with the taper coupling losses shown by the dotted line. To obtain an estimate of the gain waveguide loss, we simply subtract out the coupling losses and divide by the length of the waveguide as determined by the mask layout. This calculation gives an estimated loss of 1.5 dB/cm at 1900 nm, as shown in Figure 4-10(b). Another estimate is obtained by measuring a passive spiral waveguide, which has a length of 12.9 cm. Following the same procedure, measurement of the throughput yields an estimate of 0.9 dB/cm for the loss (although this calculation as-
Figure 4-10: Measurement of gain waveguide test structure. (a) Measured throughput of the 1.57-cm-long straight test structure (blue), 12.9-cm-long spiral waveguide (red), and coupling loss extracted from DN taper measurement (dotted line). (b) Extracted gain waveguide loss per unit length from the straight (blue) and spiral (red) throughput data.

Assumes that losses in the bends are identical to losses in the straight waveguides). Due to the uncertainties inherent in these two measurements, they should perhaps be considered as rough estimates indicative of the range of possible values of the waveguide loss. The measurement of the short structure is somewhat more sensitive to the exact coupling efficiency on and off the chip, and the measurement of the spiral involves the presence of large waveguide bends that complicate the picture somewhat. However, the spiral measurement can usefully serve as a lower bound, since the bend waveguides are unlikely to have lower loss than the comparable straight sections.

An important question is why the waveguide losses are so high in the first place, compared to what is expected from measurements of the constituent material losses. By far the largest fraction of the mode is contained in the Al₂O₃ layer, with a confinement factor of approximately 80%. The background loss of the Al₂O₃ films is routinely measured to be very low, on the order of 0.1-0.2 dB/cm. The nitride losses are generally much higher, although the confinement factor in this layer is only 3%, so it cannot contribute significantly to the waveguide loss. One possible explanation is roughness at the interfaces between material layers, due to fabrication imperfections. The interface which is likely to have the largest impact on waveguide loss is the bottom of the photonic trench, as this is the material junction at which the field intensity is highest for the optical mode. Figure 4-11(a) shows a magnified image of the electric field intensity of the mode at 1900 nm, with the vertical profile of the intensity at the center of the mode shown in Figure 4-11(b). The nitride layer
Figure 4-11: (a) Magnified electric field intensity profile at 1900 nm. Dashed line denotes the center of the mode distribution. (b) Magnitude of the electric field intensity as a function of vertical position, at the center of the mode. The nitride layer is shaded in orange, and the alumina layer is shaded in green. The bottom of the trench is denoted by the dashed line.

is shaded in orange, and the Al₂O₃ layer is shaded in green, with the position of the bottom of the trench denoted by the dashed line. It is clear from the plot that the field intensity is quite high at that interface, such that any roughness due to random fluctuations in the etch depth would have an outsized impact on the loss. This could be investigated by means of atomic force microscopy, to characterize the surface roughness at the bottom of the trench prior to Al₂O₃.

In addition, we qualitatively observe in thulium-doped DFB and DBR lasers based on similar waveguide designs that the laser threshold and output power are significantly improved when the photonic trench is removed from the fabrication process (these structures consist of straight gain waveguides without any transitions or edge couplers). In those devices, after depositing the FN layer, a 200 nm layer of oxide is deposited on the wafers which is subjected to chemical-mechanical polishing (CMP). Compared to the fabrication process involved with the photonic trench, the CMP oxide layer is expected to have much greater uniformity and less surface roughness. The evidence therefore suggests that the photonic trench is causing a significant increase in the waveguide loss, possibly due to the interface between the oxide and the alumina at the bottom of the trench. It is also possible that roughness at the trench sidewalls is affecting the mode propagation, although this is less likely due to the fact that the trench is 70 μm wide and the mode is approximately 5 μm wide. Some further contribution to the waveguide loss may also be caused by roughness at the sidewalls of the nitride pieces, though given the relative magnitude of the field intensity
this contribution is expected to be small compared to that caused by the trench bound-
ary. Another possibility is that the nonuniform topography of the trench causes cracking or
some other form of degradation in the aluminum film, such that the background loss of the
material is increased for trench waveguides compared to those without the trench.

4.4 Trench Transition

4.4.1 Component Design and Function

The boundary of the trench region introduces a sharp discontinuity in the layers which makes
efficient coupling of light across the boundary difficult. There are two broad approaches to
this problem: first, the mode can be slowly and adiabatically transitioned under the edge,
such that the light is coupled out from the side of the trench region. Or second, prior to the
trench boundary the mode must be confined such that the overlap with the gain material
is negligible, in which case traversing the junction at normal incidence will not introduce
additional losses. An image of the layout of two devices illustrating these design methods,
which we refer to as the horizontal and vertical transitions, is shown in Figure 4-12. The
horizontal transition method results in a very long structure, due to the necessity of keeping
the transition adiabatic. In practice, it is very difficult to achieve this transition adiabatically,
and a non-negligible fraction of the mode will be coupled to higher-order trench modes or
scattered from the interface, resulting in unacceptable losses. Instead, we pursue the vertical
transition method, and all further mention of the trench transition component will refer to
this type of device. The vertical trench transition was originally designed by C. Poulton,

![Diagram](image)

Figure 4-12: Mask layouts of two trench transition designs, shown from the top-view. (a) Adiabatic horizontal
transition device using FN(green) and SN(brown) layers. The trench layer is shown in pink. (b) Vertical
transition device using BN(red) and FN layers. Waveguide cross-sections at various points (marked by dashed
arrows) along the device illustrate how the waveguide evolves. Layer cross-sections are colored similarly to
Figure 4-4.)
the simulations and measurements presented here were performed by the thesis author.

In order to minimize the mode confinement in the trench region, we introduce a thick “bottom nitride” (BN) layer beneath the first nitride (FN) layer used in the gain waveguide. The thickness and vertical separation of the BN layer relative to the FN layer are chosen so as to minimize the interaction of the mode with the gain material. In this way we can cross the trench boundary without incurring scattering losses or coupling to unwanted trench modes. The thickness of the BN layer is 400 nm, and the separation between the BN and FN layers is 450 nm. The BN waveguide width at the trench boundary is chosen to be 2.5 μm, in order to maintain single-mode operation at the signal wavelength of 1900 nm, and also to ensure sufficiently high confinement in the BN layer for both the pump and signal modes.

In the first section of the transition, after crossing the trench boundary, we introduce a FN waveguide above the BN waveguide, which is tapered up in width from the minimum of 100 nm (determined by the fabrication resolution) to 2.0 μm while the BN width is held constant. The length of this section is chosen to be 50 μm. In the next section of the device, the FN width is held constant while the BN waveguide is tapered down to the minimum width of 200 nm, over a length of 300 μm. The length optimization for the two sections was simulated using the eigenmode expansion propagation solver within the Lumerical software, and the results are shown in Figure 4-13. Figure 4-14 shows the signal mode at the beginning and end of the transition, as well as the field intensity along the center of the device as the mode propagates. As can be seen from the figure, the mode is first coupled up from the BN layer into the FN layer as the BN waveguide is tapered down, and finally up into the trench

![Figure 4-13: Simulated transmission of fundamental mode for the pump and signal as a function of transition device length. (a) Transmission versus length of the first transition section, with the second section held constant at 300 μm. (b) Transmission versus length of second transition section, with the first section held constant at 50 μm. Circles mark the chosen section lengths for the device.](image-url)
Figure 4-14: Electric field intensity for the signal mode at the beginning (a) and end (b) of the trench transition component. (c) Field intensity along the central axis of the device, showing how the mode evolves as a function of propagation distance.

region. At the end of the transition the mode confinement in the BN layer is negligible and so the waveguide can be safely cut. The device is simulated to couple 99.7% of power from the input mode into the output mode at 1900 nm and 99.4% at 1600 nm.

4.4.2 Device Performance: Experimental Results

To measure the performance of the fabricated trench transition, we laid out several rows of devices back-to-back, with an increasing number of devices in each row, similar to a cutback measurement. We fabricated four rows of devices, starting from 10 transitions in the first row and increasing by 10 in each subsequent row. After depositing a passive Al\textsubscript{2}O\textsubscript{3} film (no thulium doping) on top of the chip, we then measure the transmission through each row using a tunable laser source. Light is coupled onto the chip using lensed fibers with a 3 \( \mu \text{m} \) spot size, and we use inverse nitride tapers on the chip to maximize the coupling. After measuring the transmission of all rows, we use a least-squares fit to extract the loss per device. This method automatically calibrates out the coupling losses on and off the chip.

One subtle difference with the standard cutback technique, however, is that in this case each row must have the same total propagation length, which is set by the size of the reticle. So after propagating through some number of transitions, the light must travel the rest of the distance to the chip facet in a nitride waveguide. The least-squares fit will then return the difference between the loss accumulated through 10 transitions and that accumulated over the equivalent length of nitride waveguide. The propagation loss in the nitride waveguide was therefore measured separately and calibrated out in order to provide
Figure 4-15: Measured insertion loss of the trench transition at 1900 nm. (Left) Measured throughput for each row, before coupling loss calibration. The $N = 10$ row was damaged, and is not shown here. (Right) Insertion loss per transition obtained with a least-squares fit, after calibrating out nitride waveguide losses.

Figure 4-16: Measured insertion loss of the trench transition at 1600 nm. (Left) Measured throughput for each row, before coupling loss calibration. (Right) Insertion loss per transition obtained with a least-squares fit, after calibrating out nitride waveguide losses.

an accurate assessment of the transition performance. The result at 1900 nm is shown in Figure 4-15, with an average insertion loss of 0.01 dB per transition. The result at 1600 nm is shown in Figure 4-16, with an average insertion loss of 0.05 dB per transition.

### 4.5 Gain Waveguide Transition

#### 4.5.1 Component Design and Function

Following the trench transition, one further transition component is needed to transform the waveguide from the single-piece FN waveguide shown in Figure 4-14b to the segmented FN structure that constitutes the gain waveguide. We refer to this component as the gain
waveguide transition. The transition is formed by introducing small FN pieces at either side of the central FN waveguide, and then tapering these up in width as the central piece is tapered down. The top view of this device is shown in Figure 4-17(a), and Figure 4-17(b) shows how the signal mode is pushed up into the gain region as it propagates through the transition. The length optimization is shown in Figure 4-18. The chosen device length of 250 μm was simulated to give 99.9% transmission for the pump and signal.

Figure 4-17: (a) Top-view mask layout of the gain-waveguide transition component. (b) Field intensity of the signal mode along the central axis of the device.

Figure 4-18: Simulated transmission of the gain-waveguide transition for the pump and signal wavelengths, as a function of device length.

### 4.5.2 Device Performance: Experimental Results

The transition loss was measured using the same method described for the trench transition in the previous section, and the measured results around 1900 nm are summarized in Figure 4-19. The average insertion loss per transition was found to be about 0.02 dB. The results at 1600 nm are shown in Figure 4-20, with an average insertion loss per transition of 0.05 dB.
4.6 Compact Bend for Segmented Architecture

For the segmented architecture, we make use of the trench transition to couple light out of the active material and into the BN layer, so that the bend can be implemented more compactly. In addition, we make use of a more sophisticated bend design in order to minimize the losses associated with mode mismatch at the bend junctions. The fundamental cause of mode mismatch losses is that the radius of curvature abruptly changes at the entrance of the bend, and the mode in the bend is not identical to the mode in the straight waveguide. To eliminate this loss mechanism, the curvature should be smoothly turned on, such that the radius is effectively infinity at the entrance to the bend (matching the straight waveguide). We use a bend based on the Euler spiral, also referred to as the Cornu spiral or clothoid
function, in which the curvature increases linearly as a function of path length. The curve can be parameterized as:

\[ x(t) = a \int_0^t \sin(u^2/2)du \]  \hspace{1cm} (4.2a)

\[ y(t) = a \int_0^t \cos(u^2/2)du \]  \hspace{1cm} (4.2b)

The radius of curvature is then given by \( R = a/t \), where \( a \) is a scaling variable. We refer to this structure as the Euler bend, the mask layout is shown in Figure 4-21. The Euler bend was designed by D. Vermeulen and characterized by the thesis author. The results of a cutback measurement for the insertion loss are shown in Figure 4-22. The oscillation in the observed insertion loss is similar to that observed in the DN paperclip and trench transition measurements. The fact that the magnitude of the oscillation is the same for both test structures, and has the same magnitude as in the measurements of other (very different) component test structures, suggests that the reflection is not internal to the integrated chip. Further, as will be seen in a later section, the same test structures measured with a tunable 1550 nm laser do not exhibit any form of fringing. The cause may be some form of power fluctuation during the course of the measurement by the tunable 1900 nm source, which has a relatively slow tuning speed, or else may be due to vibrations in the coupling fiber. Considering the mean of the oscillation then, the loss per bend is estimated to be 0.04 dB.

Figure 4-21: Mask layout of the Euler bend test structure. A magnified image of the bend is shown at right with approximate dimensions marked.
Figure 4-22: Measured insertion loss of the compact Euler bend. (Left) Measured throughput for two test structures, before coupling loss calibration. (Right) Insertion loss per bend after calibrating out nitride waveguide losses.

4.7 Pump-Signal Combiner

In general, it is preferable to have a separate input port for the pump light so that the edge coupler can be optimized for maximal coupling at the pump wavelength. The alternative is to have a single edge coupler that couples the pump light onto the chip and the signal light off the chip, which then also requires transmitting the pump light through the grating reflector in order to enter the laser cavity. Since the gratings usually have much stronger scattering losses at shorter wavelengths, this approach would be likely to incur significant loss at the pump wavelength. A better approach is therefore to have a wavelength combiner downstream of the grating, such that it is not in the pump path. In addition, the trench transition described in section 4.4 will not work well for the case of 790 nm pumping, since the width of the BN layer is large enough to support several higher-order modes at 790 nm. This significantly increases the risk of coupling to higher-order modes in the BN waveguide, which will not couple properly to the desired mode in the gain region. Therefore any pump-combining element that is designed for 790 nm will also have to be downstream of the trench transition. There are a number of different ways to approach the design of this component, which have different advantages depending on which pump wavelength is used.

First, we could use a mode-evolution approach, in which the fundamental modes for the pump and signal are spatially separated at the input of the device, and the waveguide cross-section adiabatically evolves into one in which the modes are spatially overlapped. This approach is easier to achieve when the pump and signal wavelengths are significantly
different (as in the case of 790 nm pumping), because it is relatively simple to design a waveguide that has very different mode distributions for the two wavelengths.

Second, we could instead use an evanescent coupling approach, in which two waveguides are brought close together as in a directional coupler, but such that the coupling coefficient is close to zero for one wavelength (this would most likely be the pump wavelength, as the mode will be more confined in the waveguide and the mode overlap with the second waveguide can be made negligible). In this case the pump light will propagate through, remaining in its original waveguide, and the signal mode will couple across to the other waveguide, with the length of the device determining the fraction of light that is coupled. This approach has the advantage of being relatively simple to design and to fabricate, although in general it can be more susceptible to small variations in fabrication.

Third, we could use a Mach-Zehnder interferometer, in which a coupler splits the input onto to paths, one of which has a (wavelength-dependent) phase delay with respect to the other. The two arms are then recombined, and the accumulated phase will determine the fraction of power in each output arm. The phase difference can in principle be realized through a path-length difference or by using waveguides with different propagation constants for the two arms, in practice since it is difficult to control the exact propagation constant of a waveguide in fabrication, implementing a path-length difference is likely to be the more robust method. The Mach-Zehnder approach is essentially the only viable option when the wavelengths to be combined are relatively close together, since the other two approaches rely on the mode properties for the two wavelengths being sufficiently different.

4.7.1 Component Design: 1600 nm Pumping

Due to the relative ease of designing the other components in the cavity for use at 1600 nm, our laser architectures are primarily designed for 1600 nm pumping. In particular, the transition components in the gain region will work well at this wavelength, which enables us to implement the pump-signal combiner outside of the trench. This is advantageous because it avoids adding another component into the cavity that would have the potential risk of coupling to higher-order trench modes. The pump and signal wavelengths are far enough apart that the evanescent-coupling approach is feasible for this component, which is less risky than the Mach-Zehnder approach due to the sensitivity of the phase delay section to fabrication variations. However, designing a coupler that will couple zero percent of the
pump while coupling 100% of the signal power will result in a very long device, and the longer the device the more susceptible it will be to fabrication variations. Therefore we employ a hybrid approach, using a Mach-Zehnder interferometer that has zero phase delay, essentially two directional couplers back-to-back.

\[
\begin{bmatrix}
E_2 \\
E_4
\end{bmatrix} = 
\begin{bmatrix}
t_{12} & t_{32} \\
t_{14} & t_{34}
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_3
\end{bmatrix}
\]

Figure 4-23: Visualization of pump-signal combiner device. Port 1 serves as the pump input port, Port 3 serves as the signal input port, and Port 2 serves as the combined output port. (Bottom) Mask layout of the combiner device.

Figure 4-23 diagrams the design approach for the four-port device, with the amplitude transfer matrix for the device shown at top right. The transfer matrix for a single directional coupler is given by

\[
A = \begin{bmatrix}
t & -j\kappa \\
-j\kappa & t
\end{bmatrix}
\]  \hspace{1cm} (4.3)

where \( t \) is the field amplitude transmission coefficient and \( \kappa \) is the field amplitude coupling coefficient. Therefore the amplitude transfer matrix of the combiner will be \( A \times A \):

\[
\begin{bmatrix}
t_{12} & t_{32} \\
t_{14} & t_{34}
\end{bmatrix} = 
\begin{bmatrix}
t^2 - \kappa^2 & -j2t\kappa \\
-j2t\kappa & t^2 - \kappa^2
\end{bmatrix}
\]  \hspace{1cm} (4.4)

The power transmission through the device (port 1 to port 2) will then be \( T_{12} = |t_{12}|^2 = (t^2 - \kappa^2)^2 \), and the power transmission across the device (port 1 to port 4) will be \( T_{14} = |t_{14}|^2 = 4t^2\kappa^2 \). For a lossless coupler, \( t^2 + \kappa^2 = 1 \), in which case \( T_{14} = 4t^2(1-t^2) = 1 - T_{12} \). The goal is therefore to design a coupler such that \( t^2 = 0.5 \) at the signal wavelength, and \( t^2 \approx 1 \) at the pump wavelength.

We choose the BN layer to implement this device, because the thicker nitride will result in strong confinement for the pump wavelength, and the coupler design can then focus primarily achieving the desired 50% coupling at the signal wavelength. The width of the
waveguides is chosen to be 1.0 \( \mu \text{m} \), in order to maintain single-mode operation for both wavelengths. With the waveguide cross-section set, the coupling ratio is then determined by the gap between the waveguides and the length of the coupling region, which we denote by \( G \) and \( L \) respectively. To calculate the coupling ratio, we first solve for the modes in an unperturbed waveguide, then use standard coupled mode theory [66, 67] to calculate the mode-coupling coefficient (per unit length) as a function of the waveguide separation. We then numerically integrate the coupling coefficient along the length of the device, taking into account the gap profile of the bend waveguides on either side of the central coupling region.

Figure 4-24(a) shows the coupler transmission \( c = t^2 \) as a function of \( G \) and \( L \), for the signal wavelength. The dashed lines represent contours on which the transmission is 50\%, which is the target value. As can be seen from the figure, there are multiple contours which satisfy the design target; the lower contour represents the condition where the input mode is coupled completely across to the opposite waveguide and then partially coupled back. To evaluate the robustness of the coupler design to variations in \( G \) and \( L \), we define a sensitivity parameter \( s \) given by:

\[
 s = \left| \frac{\partial c}{\partial G} \right| + \left| \frac{\partial c}{\partial L} \right| 
\]  

(4.5)

The sensitivity is shown in Figure 4-24(b) as a function of \( G \) and \( L \). As expected, the lower contour is significantly more sensitive, the upper contour is more robust against variations. The value of \( s \) along the contour is roughly constant in the parameter range examined here.

Figure 4-25 shows the coupler transmission for the pump wavelength, with the same contour overlaid. The pump transmission approaches \( c \approx 1 \) as we move along the contour in the direction of increasing \( L \), however, the longer the device, the more susceptible it will be to fabrication variations. Therefore we choose \( L = 100 \mu \text{m} \) and correspondingly \( G = 1.62 \mu \text{m} \) for the design point, marked on the figures.

Figure 4-26(a) shows the coupling ratio of the directional coupler at the design point, as a function of wavelength. The coupling ratio is simulated to be 50\% at 1900 nm and 2.7\% at 1600 nm. Figure 4-26(b) shows the resulting simulated transmission of the combiner device, with two identical couplers back-to-back. The transmission \( T_{12} \) is found to be 89\% at the pump wavelength, and \( T_{14} \) is 100\% at the signal wavelength, as desired.
Figure 4-24: (a) Simulated coupler transmission $c(G, L)$ at 1900 nm. Dashed lines represent the contours on which $c = 0.5$. (b) Simulated sensitivity $s(G, L)$, with $c = 0.5$ contour overlaid.

Figure 4-25: (a) Simulated coupler transmission $c(G, L)$ at 1600 nm. Dashed lines represent the contours on which $c = 0.5$ at 1900 nm. (b) Magnified version with colormap rescaled to accentuate differences along the contour.

Figure 4-26: (a) Simulated coupling ratio ($s^2$) of directional coupler as a function of wavelength. (b) Simulated transmission of complete combiner device from Port 1 to Port 2 (red) and Port 3 to Port 2 (blue).
4.7.2 Device Performance: Experimental Results

To characterize the performance of the fabricated pump-signal combiner, we laid out a coupler branch-tree, as shown in Figure 4-27. An input fiber was coupled to the top left port, and the transmission at each of the output ports was measured. The coupling ratio was then extracted using a least-squares fit. Similarly to the transition test structures described in previous sections, the waveguide loss of the connector waveguides was also calibrated out. The measured results at 1900 nm are shown in Figure 4-28; the extracted coupling ratio was 63%, which results in an insertion loss of 0.35 dB for the combiner device between port 3 and port 2. Figure 4-29 shows the measured results at 1600 nm; the extracted coupling ratio was 3.5% and the insertion loss between port 1 and port 2 was therefore 0.6 dB.

Compared to the design target, the coupling ratio at 1900 nm deviated fairly significantly, but thankfully due to the overall device design the impact of this shift was not drastic in terms of insertion loss. The source of the discrepancy is likely to be fabrication variations in the cross-section of the waveguide, as small differences in either the thickness or the width can result in a non-trivial difference in the propagation constant, which in turn determines the coupling ratio. It is also possible that the refractive index of the nitride at 1900 nm...
Figure 4-29: Measured performance of pump-signal combiner at 1600 nm. (Left) Directional coupler throughput for each row, before coupling loss calibration. (Right) Extracted coupling ratio for a single coupler and associated Mach-Zehnder combiner insertion loss, in blue and orange respectively.

is slightly different from the simulated value, since the measured values used to determine a Sellmeier fit are at much shorter wavelengths. A reduction of as little as 1% in the refractive index from the expected value would result in a 10% increase in the coupling ratio at 1900 nm. Future design iterations of this device would benefit greatly from an accurate characterization of the refractive index at longer wavelengths.

4.8 Dispersion-Compensating Grating

The theory and design principles for the chirped-apodized gratings were discussed in Chapter 3 and will not be repeated here, all that is involved is a translation of the center wavelength and re-optimization of the chirping and apodization parameters. For the spiral laser architecture, the grating is implemented in the FN layer; for the more recent segmented architecture, we included laser variations using updated broadband BN grating designs. The FN gratings were originally designed by Purnawirman, the simulations of those devices reported here were performed by the thesis author.

4.8.1 Component Design: FN Gratings

The width of the perturbation blocks was 1.4 μm, and the width of the central waveguide was tapered up from 860 nm to 1.278 μm along the length of the device. The chirp and apodization profiles are shown in Figure 4-30; the propagation constant was linearly chirped, and the grating strength followed a quadratic function. Three gratings were designed, with dif-
Figure 4-30: Simulation of 1900 nm FN grating device with a linear chirp and quadratic apodization profile. (a) Propagation constant $\beta$ as a function of position $z$ along the length of the device. (b) Grating coupling strength $\kappa$ and corresponding gap between the central waveguide and perturbation blocks as a function of position.

Figure 4-31: Simulated performance of three FN grating devices designed for 1900 nm, with lengths 360 $\mu$m (blue), 500 $\mu$m (red), and 760 $\mu$m (green). (a,c) Reflectivity and group delay as a function of wavelength across the band of interest. (b,d) Reflection and group-delay dispersion in the usable portion of the grating spectrum.
different GDD target values for compensation of the laser cavity dispersion. The simulated performance of the designs is summarized in Figure 4-31. The gratings are simulated to have >80% reflection over a 15-nm bandwidth centered at 1900 nm, with a flat GDD profile across the wavelength range of interest. The three design variations correspond to GDD target values of 0.085 ps/nm, 0.125 ps/nm, and 0.17 ps/nm. Figure 4-32 shows the measured transmission through two of the FN grating devices as a function of wavelength. The ‘s560’ design corresponds to the design shown in blue in Figure 4-31, and the ‘s780’ device corresponds to the design shown in red. Assuming minimal scattering losses, the transmission curve suggests that the reflectivity is approximately 93% across a bandwidth of 12 nm.

4.8.2 Component Design: Broadband BN Gratings

The broadband gratings were designed to have a flat GDD profile across the entire gain band of thulium, in order to support the formation of ultrashort pulses within the laser cavity. The width of the central BN waveguide was 900 nm and the width of the perturbation blocks was 1.6 μm. Four gratings with different target GDD values were designed; the chirp parameters and GDD targets are summarized in Table 4.2. Figure 4-33 shows the chirp and apodization profiles for the grating variations, along with the associated waveguide gap profile. Figure 4-34 shows the simulated reflection, group delay and GDD for each of the four grating designs. Each of the four devices is simulated to have > 80% reflection over a 100-nm bandwidth centered at 1900 nm, with the longer devices anticipated to deliver > 90% reflection over that same wavelength band.
Figure 4-33: Simulation of 1900 nm BN grating devices with a third-order polynomial chirp and raised-cosine apodization profile. (a) Bragg wavelength $\Lambda$ as a function of position $z$ along the length of the device. (b) Grating coupling strength $\kappa$ and corresponding gap between the central waveguide and perturbation blocks as a function of position.

Figure 4-34: Simulated performance of four BN grating designs: s600 (blue), s800 (red), s1000 (green), and s1200 (purple). (a,c) Reflectivity and group delay as a function of wavelength across the grating band of operation. (b,d) Reflection and group-delay dispersion in the usable portion of the grating spectrum.
4.9 Nonlinear Interferometer

In addition to using off-chip SBRs as the mode-locking element for the laser cavity, we developed a fully-integrated artificial saturable absorber by exploiting the Kerr nonlinearity in silicon nitride waveguides [68]. This approach enables a mode-locked laser architecture that is entirely contained on-chip without the need for any optical alignment or the inclusion of any exotic materials. The devices and all their constituent sub-components were designed and measured by K. Shtyrkova, a detailed theoretical and experimental treatment is presented in [16]. We briefly summarize the results here. The principle of operation is as follows: light from the input pulse is split onto two interferometer arms by a directional coupler with power transmission \( t^2 \), such that most of the power is coupled onto one arm.

The two pulses propagate along a length \( L \) of the nonlinear waveguide, reflect off of loop mirrors, and return to the input coupler. Since the two pulses have different powers, they will accumulate different amounts of nonlinear phase. When they interfere again at the input coupler, the phase difference will translate into a power-dependent reflectivity. For a device with waveguides of identical length and cross-sections in each arm, the power reflection and transmission of the NLI are given by:

\[
R = \eta^2 R_m \left[ t^4 + \kappa^4 - 2t^2\kappa^2 \cos(\Delta \phi_{NL}) \right] \tag{4.6a}
\]

\[
T = \eta^2 R_m \left[ 2t^2\kappa^2(1 + \cos(\Delta \phi_{NL})) \right] \tag{4.6b}
\]

where \( \eta \) is the power loss factor in the NLI waveguide, \( \eta = e^{-\alpha wgL} \), \( R_m \) is the loop mirror reflectivity, \( t^2 \) and \( \kappa^2 \) are the coupler transmission and coupling coefficients, and \( \Delta \phi_{NL} \) is the difference in nonlinear phase accumulated in each arm of the interferometer. Assuming a lossless coupler, \( t^2 + \kappa^2 = 1 \), in which case the differential nonlinear phase is given by:

\[
\Delta \phi_{NL} = \gamma_{NL} L_{eff}(1 + R_m \eta)(2t^2 - 1)P_m \tag{4.7}
\]

### Table 4.2: Summary of parameters in BN grating designs

<table>
<thead>
<tr>
<th>( S )</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( D )</th>
<th>( \kappa_{max} )</th>
<th>( D_{g,\lambda} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>(-55 \times 10^{-9})</td>
<td>(1.0 \times 10^{-14})</td>
<td>(4.5 \times 10^{-13})</td>
<td>(-1.2 \times 10^{-16})</td>
<td>(5.1 \times 10^4)</td>
<td>(10 \text{ fs/nm})</td>
</tr>
<tr>
<td>800</td>
<td>(-55 \times 10^{-9})</td>
<td>(3.0 \times 10^{-12})</td>
<td>(2.8 \times 10^{-13})</td>
<td>(-7.5 \times 10^{-17})</td>
<td>(5.1 \times 10^4)</td>
<td>(14 \text{ fs/nm})</td>
</tr>
<tr>
<td>1000</td>
<td>(-55 \times 10^{-9})</td>
<td>(1.0 \times 10^{-11})</td>
<td>(1.6 \times 10^{-13})</td>
<td>(-2.5 \times 10^{-17})</td>
<td>(5.1 \times 10^4)</td>
<td>(18 \text{ fs/nm})</td>
</tr>
<tr>
<td>1200</td>
<td>(-55 \times 10^{-9})</td>
<td>(1.0 \times 10^{-11})</td>
<td>(1.05 \times 10^{-13})</td>
<td>(-1.0 \times 10^{-17})</td>
<td>(5.1 \times 10^4)</td>
<td>(22 \text{ fs/nm})</td>
</tr>
</tbody>
</table>
where $\gamma_{NL}$ is the effective nonlinearity parameter for the waveguides, $L_{eff} = (1 - \eta)L/\alpha_{nwg}$ is the effective nonlinear interaction length, and $P_{in}$ is the peak power at the input of the device. The mask layout of the integrated device is shown in Figure 4-35.

![Diagram](image)

Figure 4-35: Mask layout of the NLI test structure, with constituent sub-components labeled. Device as shown is not to scale.

### 4.9.1 Component Design

The key parameters that figure into the design of the device are the interferometer waveguide cross-section, the coupling ratio, and the length of the interferometer arms. The waveguide cross-section is chosen so as to maximize the effective nonlinearity while simultaneously minimizing the waveguide dispersion, which would broaden the input pulse and reduce the effectiveness of the device. With these constraints, the optimum was found to be a double-nitride waveguide with a width of 1.5 $\mu$m. The coupler splitting ratio determines the modulation depth of the device, and together with the effective interaction length will determine the differential nonlinear phase $\Delta \phi_{NL}$. We included three design variants on the splitting ratio, 90/10, 93/7 and 96/4. The optimum length of the interferometer arms will be a balance between maximizing the interaction length and minimizing the loss introduced to the laser cavity by the component. For the spiral architecture we choose a length of $L = 2.25$ cm in the cavity, and for the segmented architecture we choose a length of $L = 1.57$ cm. The NLI test structures have a length of $L = 2.35$ cm.

### 4.9.2 Device Performance: Experimental Results

The nonlinear interferometer was characterized using pulses from an optical parametric oscillator (OPO) centered at 1.9 $\mu$m wavelength. The pulse duration was 200 fs and the OPO repetition rate was 80 MHz. In order to avoid dispersively broadening the pulses, an aspheric lens was used to couple the pulses onto the chip, the output was then collected
from the DN edge coupler with a lensed fiber. The input coupling loss was measured to be 6.85 dB, and the output coupling loss was 2.3 dB, as measured previously in Section 4.2. To investigate the nonlinear behavior of the device, the input power was varied across a large range. The results are shown in Figure 4-36, a more complete discussion of the experiment is given in [16].

All the individual sub-components were measured with independent test structures; we can therefore compare how well the complete device matches the expected theoretical performance. Considering Eq. 4.6b, the maximum transmission will occur at $\Delta \phi_{NL} = 0$, which for a lossless coupler will be given by:

$$T_{max} = \eta^2 R_m 4t^2 (1 - t^2)$$  \hspace{1cm} (4.8)

However, the output port of the NLI test structure is coupled through a long length of nitride waveguide, in order to route the output to the opposite side of the chip. The maximum transmission as measured at the output of the structure will be then reduced by a factor of $e^{-\alpha_{wvg}L_{out}}$. The loop mirror reflection was measured to be 98%, and the NLI coupler transmission was measured to be $t^2 = 0.91$. Using the measurement of the DN waveguide loss extracted from the taper test structure, $\alpha_{wvg} = 0.85$ dB/cm, we calculate $e^{-\alpha_{wvg}(2L + L_{out})} = 0.252$. Therefore the maximum transmission measured at the output of the NLI test structure should be $T_{max} = 0.081$.

Figure 4-36(a) shows the measured power at the output of the chip as a function of the input power, after calibrating out the coupling losses. The transmission factor $P_{out}/P_{in}$ is shown in Figure 4-36(b), with a maximum value of $T_{max} = 0.075$ for 1W of input peak power, which is in good agreement with the expected value. The position of the peak transmission, or rather, the absence of a minimum at $P_{in} = 0$, suggests that there is some residual linear phase bias in the interferometer, likely caused by small fabrication differences in the two waveguide arms. By adding heaters into the structure, we can control the linear phase bias to our advantage, as this enables control over the slope of the transmission curve at the $P_{in} = 0$ point. The slope is related to the self-amplitude modulation coefficient, which plays a critical role in shaping the pulse for soliton mode-locking.
4.10 Dispersion Budget

In order to enable stable mode-locking, we must design the laser cavity such that the net dispersion is anomalous. When choosing the target GDD values for the dispersion-compensating gratings, we therefore simulate the contributions of each element in the cavity and sum them up for each laser architecture. For the gain waveguide, we use the dispersion given by the intermediate estimate from the single-pole Sellmeier fit, which gives a GVD of 60 fs$^2$/mm at 1900 nm. In the spiral lasers, the dispersion of the bend waveguide is approximately the same as the straight section, so this is not treated as a separate component. The dispersion of the compact Euler bend is estimated by calculating the dispersion of the waveguide cross-section at the entrance to the bend, and approximating the GVD as constant throughout the structure. For the trench transition, we calculate the dispersion at the entrance to the transition, which is the same cross-section as for the Euler bend, and approximate the GVD as constant throughout the structure. This will yield an overestimation of the GDD for that component, since the waveguide cross-section at the exit of the transition is approximately the same as that of the gain waveguide, and has a GVD of 140 fs$^2$/mm. A more precise approximation might be to take the average of these two dispersion values, however, we prefer to take conservative estimates in order to ensure that the net cavity GDD is anomalous. The dispersion of the gain waveguide transition is approximately the same as for the gain waveguide, so this is not treated as a separate component; its length contribution is included as part of the gain waveguide. The waveguide cross-sections of the
pump/signal combiner and nonlinear interferometer are constant throughout, so there is no approximation involved.

The dispersion budget for the spiral and segmented laser architectures are shown in Table 4.3 and Table 4.4, respectively. For the SBR laser cavities, we omit the dispersion contribution of the DN waveguide, the cavity GDD will then be given by the subtotal in the penultimate row. We included several laser variations using different dispersion-compensating gratings, for both the spiral and segmented architectures. The net GDD in the cavity is shown in Table 4.5. In choosing the target GDD values for the broadband gratings (which were designed for smaller dispersion values than the FN gratings), we formulated the cavity dispersion budgets using the single-pole Sellmeier fit (‘Fit 1’ in Table 2.1) to calculate the dispersion of the gain waveguide. Under this assumption, all but one of the cavity configurations will have net anomalous dispersion, with several of the segmented laser cavity variants having net GDD close to zero. If the three-pole Sellmeier fit is used instead (‘Fit 3’ in Table 2.1), the cavity GDD will be more anomalous in all cases, these estimates are also included in Table 4.5. For the segmented architecture, the cavity dispersion can be further fine-tuned by adjusting the thickness of the Al₂O₃ film, since none of the constituent components are particularly sensitive to the film thickness. For the spiral lasers, there is less room to maneuver due to the increased pump loss in the waveguide bend for thicker films.
Table 4.3: Dispersion budget for spiral laser cavity at 1900 nm. Component lengths are given as round-trip (RT) distances. Abbreviations are as follows: GW – gain waveguide, TT – trench transition, WDM – wavelength multiplexer (pump/signal combiner), DN wvg – double-nitride waveguide within the nonlinear interferometer.

<table>
<thead>
<tr>
<th>Component</th>
<th>GVD [fs²/mm]</th>
<th>RT Length</th>
<th>GDD [fs²]</th>
<th>Subtotal [fs²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>60</td>
<td>258 mm</td>
<td>1.55 x 10⁴</td>
<td></td>
</tr>
<tr>
<td>TT (×2)</td>
<td>1260</td>
<td>700 µm</td>
<td>1.76 x 10³</td>
<td>1.900 x 10⁴</td>
</tr>
<tr>
<td>WDM</td>
<td>2200</td>
<td>800 µm</td>
<td>1.76 x 10³</td>
<td></td>
</tr>
<tr>
<td>DN wvg</td>
<td>840</td>
<td>45 mm</td>
<td>3.78 x 10⁴</td>
<td>5.680 x 10⁴</td>
</tr>
</tbody>
</table>

Table 4.4: Dispersion budget for segmented laser cavity at 1900 nm. Component lengths are given as round-trip (RT) distances. Abbreviations are as follows: GW – gain waveguide, GWB – gain waveguide bend (Euler bend), TT – trench transition, WDM – wavelength multiplexer (pump/signal combiner), DN wvg – double-nitride waveguide within the nonlinear interferometer.

<table>
<thead>
<tr>
<th>Component</th>
<th>GVD [fs²/mm]</th>
<th>RT Length</th>
<th>GDD [fs²]</th>
<th>Subtotal [fs²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>60</td>
<td>116 mm</td>
<td>6.96 x 10³</td>
<td></td>
</tr>
<tr>
<td>GWB (×2)</td>
<td>1260</td>
<td>1.25 mm</td>
<td>3.15 x 10³</td>
<td></td>
</tr>
<tr>
<td>TT (×6)</td>
<td>1260</td>
<td>700 µm</td>
<td>5.29 x 10³</td>
<td></td>
</tr>
<tr>
<td>WDM</td>
<td>2200</td>
<td>800 µm</td>
<td>1.76 x 10³</td>
<td>1.716 x 10⁴</td>
</tr>
<tr>
<td>DN wvg</td>
<td>840</td>
<td>18.6 mm</td>
<td>1.56 x 10⁴</td>
<td>3.279 x 10⁴</td>
</tr>
</tbody>
</table>

Table 4.5: Summary of net GDD values for the various spiral and segmented laser cavity variations.

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Cavity GDD [fs²]</th>
<th>Grating GDD [fs²]</th>
<th>Net GDD [fs²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fit 1</td>
<td>Fit 3</td>
<td>Fit 1</td>
</tr>
<tr>
<td>Spiral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBR</td>
<td>1.90 x 10⁴</td>
<td>-350</td>
<td>-1.63 x 10⁵</td>
</tr>
<tr>
<td>NLI₁</td>
<td>5.68 x 10⁴</td>
<td>3.75 x 10⁴</td>
<td>-1.63 x 10⁵</td>
</tr>
<tr>
<td>NLI₂</td>
<td>5.68 x 10⁴</td>
<td>3.75 x 10⁴</td>
<td>-2.40 x 10⁵</td>
</tr>
<tr>
<td>Segmented</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBR₁</td>
<td>1.716 x 10⁴</td>
<td>8460</td>
<td>-1.630 x 10⁵</td>
</tr>
<tr>
<td>SBR₂</td>
<td>1.716 x 10⁴</td>
<td>8460</td>
<td>-3.450 x 10⁴</td>
</tr>
<tr>
<td>SBR₃</td>
<td>1.716 x 10⁴</td>
<td>8460</td>
<td>-2.683 x 10⁴</td>
</tr>
<tr>
<td>SBR₄</td>
<td>1.716 x 10⁴</td>
<td>8460</td>
<td>-1.916 x 10⁴</td>
</tr>
<tr>
<td>NLI₁</td>
<td>3.279 x 10⁴</td>
<td>2.41 x 10⁴</td>
<td>-1.630 x 10⁵</td>
</tr>
<tr>
<td>NLI₂</td>
<td>3.279 x 10⁴</td>
<td>2.41 x 10⁴</td>
<td>-4.216 x 10⁴</td>
</tr>
<tr>
<td>NLI₃</td>
<td>3.279 x 10⁴</td>
<td>2.41 x 10⁴</td>
<td>-3.450 x 10⁴</td>
</tr>
<tr>
<td>NLI₄</td>
<td>3.279 x 10⁴</td>
<td>2.41 x 10⁴</td>
<td>-2.683 x 10⁴</td>
</tr>
</tbody>
</table>
4.11 Full Laser Cavity Characterization

4.11.1 Pump Absorption Measurements

To experimentally validate the gain/absorption model for our laser cavities, we measured the pump absorption for both architectures. First, we measured the insertion loss of the spiral waveguide at the pump wavelength, as a function of input power. This measurement was performed by K. Shtyrkova. As the pump power is increased, the absorption due to the thulium atoms should decrease as the ground-state energy level is depopulated. The insertion loss will be determined by the background loss $\alpha_{m,p}$, and by the modal absorption given by Eq. 2.11b, which in turn is dependent on the constants $N_l$, $\sigma_{a,p}$, and $\tau_1$. The measured data is shown in Figure 4-37(a), after calibrating out the coupling losses.

However, the model parameters are somewhat coupled together for this type of measurement, so in addition we measured the segmented laser cavity both with a passive Al$_2$O$_3$ film and with a thulium-doped film of identical thickness. Subtracting out the passive losses gives a direct measurement of the modal absorption, which is shown in Figure 4-37(b) as a function of wavelength. The thulium concentration for that film was measured to be $N_l = 4.15 \times 10^{20}$ cm$^{-3}$ from a Rutherford back-scattering experiment. The input pump power was chosen to be $-3$ dBm in order to avoid saturating the absorption, in this case the measured loss can be well approximated by $\alpha_{meas} = \Gamma \sigma_{a,p} N_l$. Using the value for $\Gamma$ calculated in Table 4.1 and the measured values of $\sigma_{a,p}$ shown in Figure 2-3, we calculate

![Figure 4-37](image-url)
the expected absorption for this film and compare to the measured result. Considering the error bars in the measured cross-sections, we find that the model agrees best with the experiment at 1600 nm if we assume a value toward the upper-end of the confidence interval, \( \sigma_{a,p} = 2.7 \times 10^{-21}\text{cm}^2 \). Finally, using this value for the absorption cross-section, and using the measured value for \( \tau_1 \), we calculate the expected insertion loss for the spiral waveguide and compare to the measured result shown in Figure 4-37(a). The model agrees best with experiment if we assume \( N_t = 2.05 \times 10^{20}\text{cm}^{-3} \) and \( \alpha_{m,p} = 1.3\text{dB/cm} \). This value for the background loss is well within the estimated range of the passive gain waveguide loss discussed earlier.

### 4.11.2 CW Laser Simulations

To estimate how much intracavity power is expected for the mode-locked lasers, we make use of the gain model described in Chapter 2. The modal gain was calculated using the measured spectroscopic parameters, as well as the estimated waveguide background loss discussed earlier. To simulate steady-state laser operation, we first seed the amplifier model with a particular input pump power and a small initial power at the signal wavelength. The output signal power after a single pass is then multiplied by the grating reflectivity and passed through the amplifier again. Finally, the amplifier output is multiplied by the loss and the reflectivity of the mode-locking element (SBR or NLI). This constitutes one round-trip through the laser cavity. This calculation is iterated until the difference in the intracavity power between successive round-trips is less than 0.5\%, at this point the laser is considered to be in steady-state. Figure 4-38 shows a diagram of this procedure, as well as the simulation results for the two laser cavities.

<table>
<thead>
<tr>
<th>Gain Parameters</th>
<th>Cavity Parameters</th>
<th>Spiral SBR</th>
<th>NLI</th>
<th>Segmented SBR</th>
<th>NLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{a,p} )</td>
<td>( L_{\text{gain}} )</td>
<td>12.9 cm</td>
<td>5.8 cm</td>
<td>( R_1 )</td>
<td>0.93</td>
</tr>
<tr>
<td>( \sigma_{a,s} )</td>
<td>( R_1 )</td>
<td>0.93</td>
<td>0.93</td>
<td>( L_{\text{NLI}} )</td>
<td>22.5 mm</td>
</tr>
<tr>
<td>( \sigma_e )</td>
<td>( c_{\text{ML}} )</td>
<td>0.4</td>
<td>0.391</td>
<td>( R_2 )</td>
<td>1.0</td>
</tr>
<tr>
<td>( \tau_1 )</td>
<td>( R_2 )</td>
<td>1.0</td>
<td>0.91</td>
<td>( N_t )</td>
<td>3.0 \times 10^{20}\text{cm}^{-3}</td>
</tr>
<tr>
<td>( \alpha_{m,p} )</td>
<td>( c_{\text{ML}} )</td>
<td>0.4</td>
<td>0.391</td>
<td>( \alpha_{m,s} )</td>
<td>1.3 dB/cm</td>
</tr>
<tr>
<td>( \alpha_{m,s} )</td>
<td>( \alpha_{m,s} )</td>
<td>1.0 dB/cm</td>
<td>1.0</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: Parameters used to simulate CW laser operation in the SBR and NLI mode-locked cavities, for the spiral and segmented laser architectures. All parameters listed here are derived from experimental results.
Figure 4-38: CW laser simulation for the two MLL architectures. (a) Diagram of the simulation method. Symbols are as follows: $P_p$ – input pump power, $P_{s,k}$ – seed power on the kth round-trip, $G$ – amplification factor after a single-pass through the gain waveguide, $R_1$ – grating reflectivity, $c_{ML}$ – loss due to the mode-locking element, $R_2$ – reflectivity of the mode-locking element. (b) Simulated intracavity power in the spiral architecture for SBR and NLI mode-locked cavities. (b) Simulated intracavity power for the segmented laser architecture.

A summary of the parameters used in the simulation is given in Table 4.6. For the SBR cavity, $c_{ML}$ was determined by the coupling loss on/off the chip, which was measured to be approximately 2 dB. The total loss was therefore assumed to be 4 dB, in practice it may be slightly higher due to the fact that polishing the chip facet for butt-coupling may introduce additional losses. For the NLI, $c_{ML}$ was determined by the DN waveguide losses, which were measured to be 0.85 dB/cm. In the spiral architecture the NLI is 2.25 cm long, therefore the total round-trip loss is 4.1 dB. In the segmented architecture we use a shorter NLI waveguide length, and the loss is 1.7 dB. From the simulation, the spiral laser threshold is estimated to be approximately 120 mW of pump power for both cavities, and the intracavity powers are similar for both the SBR and NLI mode-locked lasers. For the segmented architecture, the laser thresholds are estimated to be 40 mW and 30 mW for the SBR and NLI lasers, respectively. The segmented NLI laser is anticipated to have a higher intracavity power than the SBR laser due to the reduction in cavity losses from using a shorter NLI waveguide.

Both segmented laser cavities are anticipated to generate significantly higher intracavity power than the spirals; this is a direct result of using a shorter gain waveguide. The back-
ground losses at the pump wavelength impose a severe limitation on the achievable laser power. To see this, consider the growth of the signal beam during one round-trip through the laser, ‘unwrapping’ the cavity to examine the impact of waveguide loss, as shown in Figure 4-39 for an input pump power of 1 W. For the spiral laser (at left), the signal beam begins to grow as it propagates through the gain waveguide on the first pass, but ceases to experience gain in the later section of the waveguide as the pump energy is consumed by absorption and background losses. This effect is dominated by the waveguide losses and not signal reabsorption due to the thulium ions, if we set $\sigma_{a,s} = 0$ in the simulation the result will look very similar. For the segmented laser, the shorter length of the gain waveguide significantly reduces the parasitic losses, and as a result the signal beam is more nearly maximized at the end of each pass through the amplifier. In this case the limiting factor is the intracavity loss due to the reflectors (primarily the mode-locking element), the positions of which are highlighted by the black dashed boxes. For simplicity the NLI is considered as a lumped-element loss. The red and blue dashed lines denote the steady-state intracavity laser power, which is the value the beam returns to after one complete round-trip. The impact of the waveguide losses is therefore seen to be significant, and future cavity designs will focus on reducing these losses to enable higher intracavity powers and pulse energies.

Figure 4-39: Intracavity power as it evolves in one round-trip through an ‘unwrapped’ laser cavity, for a pump power of 1 W. The spiral architecture is shown in (a) and the segmented architecture is shown in (b). The grating reflector is positioned at $z = L$ and the mode-locking element is positioned at $z = 2L$, highlighted by the black dashed boxes. Red and blue dashed lines denote the steady-state intracavity laser power.
4.12 Mode-Locked Laser Results

With all the constituent components characterized, we now turn to the experimental results of the full mode-locked laser devices. Spiral lasers using both SBRs and NLIs for the mode-locking element were characterized, these devices all used the FN dispersion-compensating grating. Some segmented laser variations made use of the FN gratings, and in others we implemented the updated BN broadband grating designs. Segmented lasers with NLIs were fully characterized, and those devices which used SBRs were investigated in an extended-cavity configuration which will be discussed later in this section. The mode-locking measurements for the segmented NLI mode-locked lasers and all the spiral lasers were performed by K. Shtrykova and are described in detail in [16], we briefly summarize those results here. The extended-cavity SBR experiments for the segmented laser structures were performed by the thesis author.

A diagram of the experimental setup used to measure the spiral lasers and the segmented NLI lasers is shown in Figure 4-40. The pump laser at 1600nm is amplified using a high-power erbium-doped fiber amplifier (EDFA) optimized for the telecom L-band. The EDFA output is passed through a polarization controller, then coupled onto the chip with a lensed SMF-28 fiber that had a 3-μm spot size. For the NLI mode-locked devices, the laser output was taken from the output of the NLI and coupled out on the opposite side of the chip using a lensed SM2000 fiber, also with a 3-μm spot size. The SBR cavity is mode-locked by means of butt-coupling an external SBR chip, which is mounted on a copper substrate, to the output facet of the laser chip. In order to butt-couple to the SBR, the chips must first be polished, to remove the underlying silicon substrate that juts out beneath the dicing trench. The chips are repeatedly polished with diamond lapping paper with successively smaller grain sizes until the facet is polished to optical quality. After polishing the SBR chip is aligned to the MLL chip facet using a three-axis stage together with tip-tilt adjustment. For the SBR mode-locked devices, the output was taken from the same side of the chip as the pump input, routed through the grating transmission port. The mode-locked laser output is then passed through a 50/50 fiber splitter, one port of which is measured on an optical spectrum analyzer and the other of which is sent to a photodiode. The photodiode output is then split and measured on a fast oscilloscope and an RF spectrum analyzer.
Figure 4-40: Schematic of experimental setup for measuring mode-locked lasers using (a) NLIs and (b) SBRs. Abbreviations are as follows: EDFA – erbium-doped fiber amplifier, PC – polarization-controller, OSA – optical spectrum analyzer, PD – photodiode, Oscill. – oscilloscope, RFSA – RF spectrum analyzer.

4.12.1 Spiral Architecture: Initial Results

As can be seen from Figure 4-41(a), the laser threshold is approximately 40 mW, and the average laser power is several mW at the output of the cavity. The measured threshold is quite low compared to the expected value from the laser simulation discussed in the previous section, which suggests that the model overestimated the cavity losses. It may be that the coupling on/off chip to the SBR is better than expected, or possibly the waveguide losses at the signal wavelength are toward the lower end of the estimated range. As the pump power is increased, the laser first goes into a Q-switched pulsing regime, in which large bursts of energy are emitted with an unstable amplitude and repetition rate. As the pump power is increased further, the laser exhibits Q-switched mode-locking (QSML), in which a burst of short pulses at the cavity repetition rate is emitted at intervals determined by the Q-switched rate. The optical spectrum of the CW laser operation is shown in blue in Figure 4-41(b), and the QSML spectrum is shown in orange. The repetition rate of the laser is approximately 700 MHz, as can be seen from the RF spectrum shown in Figure 4-41(c). Figure 4-41(d) shows the detected Q-switched pulse bursts, with a Q-switching rate of 850 kHz. A magnification of the Q-switched pulses reveals the individual short pulses beneath the Q-switching envelope, separated by a period of approximately 1.3 ns, which corresponds to the fundamental repetition rate of the cavity.

The measured results for the NLI mode-locked lasers are summarized in Figure 4-42. The threshold for the NLI lasers was measured to be approximately 70 mW, which is lower
Figure 4-41: Experimental results of SBR mode-locked lasers: (a) average laser power on-chip as a function of input pump power, (b) optical spectrum of QSML operation and CW laser operation, (c) RF spectrum of QSML operation after photodetection, (d) time-domain detected output and (e) magnified time-domain data showing the pulses under the Q-switching envelope. Courtesy of K. Shlyrkova [16].

Figure 4-42: Experimental results of NLI mode-locked lasers: (a) average laser power on-chip as a function of input pump power, (b) optical spectrum of QSML operation and CW laser operation, (c) RF spectrum of QSML operation after photodetection, (d) time-domain detected output and (e) magnified time-domain data showing the pulses under the Q-switching envelope. Courtesy of K. Shlyrkova [16].
than the expected value of 120 mW from the simulation, so it is likely that the model overestimates the cavity losses somewhat. However, the bias point of the NLI was unknown, if the interferometer were biased closer to peak reflection then the laser threshold would be lower than predicted by the model. These devices also exhibit Q-switching, and Q-switched mode-locking at high input pump powers.

4.12.2 Spiral Architecture: Photonic Trench Modification

Q-switching instabilities are a common problem in mode-locked laser systems that can often be reduced by increasing the intracavity pulse energy above some stability threshold [69, 70]. To this end, we endeavored to reduce the intracavity loss by modifying the photonic trench. By significantly widening the trench, we aimed to eliminate the possibility of loss due to sidewall roughness, as well as possibly reducing the impact of any degradation in the Al₂O₃ film quality due to the topography. When this was done, we first discovered that the behavior of the spiral bend at the designed film thickness of 1.1 µm was not as expected. With the removal of the trench wall, the bend exhibited significant loss which prevented any laser operation. This suggests that even at a thickness of 1.1 µm the mode in the spiral bend was partially guided by the trench, the solution was therefore to reduce the film thickness to 900 nm or below. The dispersion of the gain waveguide would then be increased (more normal), and given that the FN gratings used in the spiral lasers significantly overcompensated for the cavity dispersion, this was also desirable for potentially producing shorter pulses. The experimental results for the wide-trench NLI spiral lasers are shown in Figure 4-43. For a certain range of input pump powers, these structures appear to produce stable mode-locked pulse trains, as can be seen from the absence of the Q-switching modulation in the time-domain data. The optical spectrum broadens considerably in this operating regime, which is evidence of short pulses. The modulation of the optical spectrum suggests that there may be multiple pulses circulating within the MLL cavity, simulations indicate that there may be two pulses with a duration of approximately 800 fs. After experiencing stable mode-locking with the widened trench for the spiral lasers, we also redesigned the layout of the segmented lasers to accommodate a wider trench. The mode-locking experiments presented in the subsequent two sections are from wafers that use a 1.5-mm trench instead of the original 70-µm trench.
4.12.3 Segmented Architecture: Extended-Cavity SBR

Even though the segmented lasers were anticipated to deliver a significant improvement in intracavity power over the spiral architecture, due to the reduced length of the gain waveguide and therefore reduced cavity loss, these structures still were not able to achieve stable mode-locking in initial experiments. In an attempt to further increase the pulse energy, we investigated an extended-cavity configuration for the segmented SBR lasers, in which a passive fiber was inserted into the laser cavity between the output of the chip and the SBR. If the coupling losses at each interface are low, this setup should decrease the repetition rate of the laser without decreasing the average intracavity power, thus increasing the pulse energy. One challenge with this configuration is to avoid parasitic reflections at the interface between the extension fiber and the chip facet, which would interfere with mode-locking operation. To reduce reflections, we suspend a drop of index-matching fluid on the tip of the fiber, which then expands to cover the interface as the fiber is butt-coupled to the chip facet. To maximize the coupling to the nitride taper, we use Nufern UHNA7 high-numerical-aperture fiber, which has an NA of 0.41 and a mode-field-diameter of 3.2 μm at 1550 nm. This fiber has been estimated to have a group-velocity dispersion of approximately $1 \times 10^5$ fs$^2$/m [71], therefore these experiments focused on the laser cavities using the FN gratings (which have significantly higher anomalous dispersion). A diagram of the experimental setup is shown in Figure 4-44.

The results of the experiment with approximately 1 m of extension fiber are shown in Figure 4-45. Q-switched mode-locking operation is observed, with a fundamental repetition rate of 90 MHz and a Q-switched rate of 270 kHz. The laser threshold for this configuration...
was 150 mW of pump power on-chip, and the laser output power was approximately 220 µW on-chip when pumped with 650 mW of pump power. If we estimate the grating reflectivity as 93%, the average intracavity power is therefore about 3 mW, which would correspond to an estimated intracavity pulse energy of 35 pJ if the pulses were mode-locked. As can be seen from the data, the additional passive fiber was not able to eliminate the Q-switching instabilities. The measured laser power was rather low, which suggests that the coupling losses associated with the extension fiber were simply too high for this configuration to result

![Diagram of the experimental setup for the extended-cavity SBR laser configuration.](image)

Figure 4-44: Diagram of the experimental setup for the extended-cavity SBR laser configuration.

![Graphs showing experimental results.](image)

Figure 4-45: Experimental results for the extended-cavity configuration with a segmented SBR laser: (a) optical spectrum, (b) RF spectrum, (c) QSML time-domain data and (d) magnified QSML time-domain data showing individual pulses beneath the Q-switched envelope.
in a significantly increased pulse energy.

4.12.4 Segmented Architecture: NLI Mode-Locking

In a recent set of experiments performed by N. Singh and M. Xin, the segmented NLI lasers were found to overcome the Q-switching instabilities for a very narrow range of bias values applied to the NLI. Gold heaters were deposited on top of the chips by K. Shtyrkova and P.D. Keathley, in order to enable tuning of the linear phase bias of the interferometer. As the bias is tuned, the mode-locking properties of the NLI change, as discussed in [16]. Stable pulse trains were obtained when the NLI bias was very close to peak reflection, such that the modulation depth was small. The preliminary results of these experiments are shown in Figure 4-46, further investigation is underway to confirm and characterize the mode-locked pulses. These results were obtained in laser cavities using the narrow-band FN gratings, similar efforts to produce stable mode-locking with the broadband BN gratings were not successful. Given the uncertainty regarding the dispersion of the gain waveguide, it may be that the segmented laser cavities using the BN gratings in fact had a net normal GDD, which would make stable mode-locking extremely difficult. In future cavity designs this possibility can be easily eliminated by adjusting the BN grating designs, or potentially by replacing the NLI loop mirrors with BN gratings for increased bandwidth and anomalous GDD.

![Graphs and images](image)

Figure 4-46: Measured results for the segmented NLI mode-locked lasers at optimal bias: (a) optical spectrum, (b) RF spectrum, and (c) photograph of time-domain data.
Chapter 5

Integrated Erbium-Doped MLL: Laser Cavity and Components

5.1 Overall Laser Architecture

In addition to developing mode-locked lasers at 1900 nm using thulium gain, we also investigated using erbium gain at 1550 nm, in fact this effort began several years prior to the work at 1900 nm. Initial devices using SBR mode-locking based on the spiral architecture suffered from the same difficulties with Q-switching instabilities and high waveguide loss, and earlier versions of the segmented architecture using a horizontal trench transition experienced considerable cavity losses and coupling to higher-order gain waveguide modes due to the difficulty of designing such a transition to be adiabatic. Results and discussion of these earlier laser structures can be found in [16, 72]. After the introduction of the thick BN nitride layer, which enabled the low-loss vertical trench transition as well as the compact Euler bend, it became feasible to revisit the erbium-doped lasers with the benefit of these improvements to the segmented laser architecture. Many of the same components used in the thulium-doped segmented lasers can be reused with minimal adjustments to the design parameters, only the gratings, nonlinear interferometer, and pump/signal combiner require significant redesign and simulation in order to be adapted to the new center wavelength. The laser architecture is shown in Figure 5-1, with constituent components labeled. These structures make use of the 1.5-mm-wide photonic trench discussed previously, rather than the 70-μm-wide trench used in earlier spiral lasers. In the sections that follow we will investigate the design and performance of these components in detail.
Figure 5-1: Diagram of wide-trench segmented laser architecture for erbium-doped mode-locked lasers at 1550 nm, with constituent components labeled. The photonic trench is represented in gray.

5.2 Nitride Edge Couplers and Waveguides

Silicon nitride that is deposited using PECVD typically has an absorption peak around 1520 nm due to the residual presence of hydrogen in the material. Harmonic overtones of the Si-H and N-H vibrational modes typically appear in this wavelength region, with the exact position of the peak being dependent on the deposition conditions [73]. This is why LPCVD nitride is more often used for integrated photonics applications in the telecom C-band, because the higher temperatures associated with that deposition method tend to significantly reduce the hydrogen content in the film. However, since our fabrication process is designed with CMOS co-integration in mind, the higher temperature treatment cannot be used without destroying various other layers in the photonic stack. For example, the dopants that are used to create P-N junctions in silicon (which are the building block of integrated phase shifters, modulators, heaters, and many other important components) tend to diffuse out of the silicon layer when exposed to high temperatures. In addition, the vias that are used to contact between metal layers will melt at temperatures higher than 450°C. Therefore we have no choice but to use PECVD nitride and work around the increased propagation loss.

The double-nitride edge couplers were redesigned to match to a 3-μm spot-size mode at the signal wavelength of 1560 nm. The optimum width at the chip facet was found to be 280 nm, and the length of the taper was 100 μm. The double-nitride waveguide width was chosen to be 1.0 μm. The test structures for the transition components used edge couplers
with a width of 380 nm, designed for 1900 nm. This was due to the fact that both thulium-doped and erbium-doped lasers were included on the same chip. Therefore we measured the coupling loss of both tapers at 1560 nm, the results are shown in Figure 5-2 along with the waveguide losses for 1.5-μm-wide double-nitride (which is used as the extension waveguide in the transition test structures) and a 1.0-μm-wide BN waveguide. The measured losses for the 1.5 μm DN waveguide can then be used to calibrate the measurements of all the various transition components.

To get an estimate of the waveguide loss for 1.0-μm-wide DN, we can compare the confinement factors in the nitride for those geometries. For a width of 1.5 μm, the confinement factor in the nitride at 1560 nm is 0.590, and for a width of 1.0 μm it is 0.519. Therefore compared to 1.5-μm-wide DN, the loss for 1.0-μm-wide DN should be decreased by a factor of 0.879. In fact, if we compare the measured loss for 1.5 μm DN and 1.0 μm BN, the BN waveguide loss is reduced by almost exactly this factor. Therefore we can use the measurement of 1.0 μm BN as a decent estimate for the 1.0 μm DN waveguide loss. The absorption peak at 1520 nm is significant, as anticipated, with a maximum value of approximately 3.5 dB/cm. At the signal wavelength the waveguide loss is reduced slightly to 1.0 dB/cm, though the wavelength dependence of the loss may have an impact on the laser behavior.

5.2.1 Nitride Rings and Group-Index Measurement

In addition to paperclip-type test structures, we also included nitride ring resonators as an alternative method for characterizing the nitride loss. The rings are formed from a 1.5-
\[ \Delta f = \frac{c}{n_g L_{rt}} = \frac{c}{2\pi R n_g} \]  

where \( R \) is the radius of the ring and \( n_g \) is the group index. From the group index, we can also calculate the group-velocity dispersion of the waveguide. The results of the measurements are shown in Figure 5-4, along with the expected values from simulation, shown by the solid black line. The measurement uncertainty in the calculated group delay due to the \( \pm 10 \) pm wavelength accuracy of the tunable laser is shown by the error bars.

As can be seen from the plots, there is a substantial discrepancy between the expected
value of the group index and the value extracted from measurement. The group index is determined by the waveguide geometry and the refractive index of the constituent materials. It is possible that the waveguide thickness or width is different, due to fabrication variations. For a 1.5-μm-wide waveguide, small perturbations in the width will not have a large effect, the group index is likely to be more sensitive to the layer thickness. The dotted black line in Figure 5-4(a) shows the simulated result for a ring waveguide with a thickness of 190 nm instead of 200 nm, which corresponds to a 5% shift. Though the difference is noticeable, the magnitude of the shift is not large enough to explain the observed discrepancy with the experiment. Therefore it is likely that the refractive index of the nitride is slightly different from the expected value. The dashed black line in Figure 5-4(a) shows the simulated result when the refractive index is reduced by 3% for all wavelengths, which gives good agreement with the measured data. Given that the Sellmeier fit used to simulate the refractive index and group delay of the nitride was based on measurements of a nitride blanket wafer, which may not have the same optical properties as the final patterned nitride layers, a discrepancy of this magnitude is perhaps not unreasonable. Figure 5-4(b) shows the dispersion, calculated from the group index, and for the two simulated refractive index profiles. There is enough uncertainty in the measurement that it is difficult to conclude whether reducing the refractive index gives a better fit to the dispersion, both estimates seem to have decent agreement with the data.
5.3 Pump-Signal Combiner

Since we are using in-band pumping at 1480 nm to pump the erbium-doped laser, the pump and signal wavelengths are close enough together that it is difficult to design a waveguide with substantially different mode profiles at 1480 nm and 1550 nm. Therefore the mode-evolution and evanescent coupling approaches mentioned in the previous chapter will be impractical to implement for this laser architecture. One viable option is to use a Mach-Zehnder interferometer (MZI), in which the phase delay between the two arms is engineered to result in constructive interference for one wavelength and destructive interference for the other. The phase accumulated in each arm will be equal to $\phi_i = \beta_i L_i$, thus it is possible to introduce a phase delay by arranging for $\beta_1 \neq \beta_2$ (by manipulating the waveguide cross-section, for example) or $L_1 \neq L_2$, or some combination of these. However, fabrication variations in waveguide height or width could have a significant impact on the propagation constants, and it is not guaranteed that their difference would remain stable. Therefore we choose to implement a path-length difference, as this should result in a more robust device.

5.3.1 Component Design

The device design consists of two elements: the directional coupler, and the phase-delay section. The transfer matrix for the MZI device is given by cascading the transfer matrices of the input coupler, phase-delay, and output coupler (identical to the input):

$$
\begin{bmatrix}
  t_{12} & t_{32} \\
  t_{14} & t_{34}
\end{bmatrix} =
\begin{bmatrix}
  t & -j\kappa \\
  -j\kappa & t
\end{bmatrix}
\begin{bmatrix}
  e^{-j\beta L_1} & 0 \\
  0 & e^{-j\beta L_2}
\end{bmatrix}
\begin{bmatrix}
  t & -j\kappa \\
  -j\kappa & t
\end{bmatrix}
= e^{-j\beta L_1}
\begin{bmatrix}
  (t^2 - \kappa^2 e^{-j\beta \Delta L}) & -jt\kappa(1 + e^{-j\beta \Delta L}) \\
  -jt\kappa(1 + e^{-j\beta \Delta L}) & (t^2 e^{-j\beta \Delta L} - \kappa^2)
\end{bmatrix}
$$

The power transmission from port 1 to port 2 and port 4 is therefore:

$$
T_{12} = |t_{12}|^2 = t^4 + \kappa^4 - 2t^2\kappa^2 \cos(\beta \Delta L) \tag{5.3a}
$$

$$
T_{14} = |t_{14}|^2 = 2t^2\kappa^2(1 + \cos(\beta \Delta L)) \tag{5.3b}
$$

As mentioned previously, in the case of a lossless coupler, $t^2 + \kappa^2 = 1$, in which case $T_{12} + T_{14} = 1$. Since the MZI will be inside the laser cavity, the transmission of the signal...
wavelength is more critical to laser performance than that of the pump. The maximum value of $T_{14}$ occurs when $\Delta \phi = \beta \Delta L = n2\pi$, in which case $T_{14} = 4t^2\kappa^2$. The maximum value of $T_{12}$ occurs when $\Delta \phi = n\pi$, in which case $T_{12} = (t^2 + \kappa^2)^2$. Assuming the device is lossless, the maximum value of $T_{12}$ will always be 1 regardless of the coupling ratio. If the phase-delay is incorrect, the result is that the maximum transmission point is simply shifted to a different wavelength. Therefore we want to arrange the cavity such that the signal propagates from port 1 to port 2 and the pump propagates from port 1 to port 4 (or equivalently port 3 to port 2). That being the case, we design the directional coupler to have a coupling ratio of 50% at 1480 nm, such that $4t^2\kappa^2 = 1$, and choose $\Delta L$ to satisfy $\beta_p \Delta L = n2\pi$ and $\beta_s \Delta L = n\pi$.

The layout of the MZI is shown in Figure 5-5. In order to minimize the impact of mask discretization on the path-length difference, we introduce $\Delta L$ vertically, such that the additional waveguide sections are aligned with the rectangular grid. This way, the phase delay contributed by the bends is common to both paths, and is therefore canceled out. The dots on the schematic indicate the vertices of the circular bends, which all have the same bend radius. By implementing the MZI device in the BN layer, we take advantage of the increased confinement factor to enable smaller bend radii and therefore a smaller device footprint. For a BN width of 1.0 $\mu$m, the mode overlap between the straight and bend waveguides is calculated to be 0.9989 for a radius of 50 $\mu$m. As there are effectively six of these junctions in each arm of the interferometer, the mode mismatch is expected to contribute approximately 0.03 dB of loss to the device. The coupler is designed using standard coupled-mode theory, similar to devices mentioned in previous chapters. The

![Figure 5-5: Mask layout of the MZI device. Black dots indicate the vertices of the circular bends. (Inset) Magnified region where the additional waveguide length is implemented.](image-url)
coupler parameters are summarized in Figure 5-6(a). The s-bend separation waveguides are given by \([S_x, S_y] = [40, 2] \mu m\), which corresponds to a minimum radius of curvature of 80 \(\mu m\). Figure 5-6(b) shows the simulated coupling ratio \(\kappa^2\) as a function of wavelength, with a coupling ratio of 48\% and 70\% at 1480 nm and 1560 nm, respectively. Using these values for \(\kappa^2\), we then calculate the propagation constants at the wavelengths of interest and substitute into the expressions for \(T_{12}\) and \(T_{14}\) to determine the optimal value for \(\Delta L\). In order to achieve the most robust design, the smallest feasible \(\Delta L\) was chosen. The results are shown in Figure 5-7, from which the design target is seen to be \(\Delta L = 7.29 \mu m\).

![Figure 5-6: (a) MZI coupler design: \(G = 580 \text{ nm, } L = 20 \mu m, S_x = 40 \mu m, S_y = 2 \mu m\). (b) Simulation of MZI coupler as a function of wavelength.](image)

![Figure 5-7: (a) Simulation of MZI transmission as a function of \(\Delta L\). (b) Magnified version centered at the target value of \(\Delta L = 7.29 \mu m\).](image)
5.3.2 Device Performance: Experimental Results

First, the directional coupler was characterized separately using a branch-tree test structure similar to those described previously. The measured results are summarized in Figure 5-8. After calibrating out the effects of fiber coupling and propagation through the extra length of nitride waveguide needed to match the length of the chip, we find that the coupler is nearly lossless, i.e. $t^2 + \kappa^2 \approx 1$ to within the precision of the measurement. However, the measured splitting ratio is significantly different from the design target, which is similar to other BN directional couplers discussed previously. This will result in some additional insertion loss at the pump wavelength, but should not affect the insertion loss for the signal.

Next, the full MZI device was characterized. Three MZI test structures with different values of $\Delta L$ were measured, in order to determine whether and in which direction the phase delay had deviated from the expected value. The mask layout for the test structures is shown in Figure 5-9. The fiber coupling loss and spacer nitride waveguide losses were measured with separate test structures and calibrated out of the MZI measurement; the

Figure 5-9: Mask layout of MZI test structures.
Figure 5-10: Measured insertion loss of MZI test structures with different phase delays.

Experimental results are shown in Figure 5-10. Several conclusions can be drawn from this data. First, the wavelength at which $T_{14}$ is minimized (maximum insertion loss in the figure) is shifted by approximately 15 nm with respect to the expected value. For $\Delta L = 7.29 \mu m$, the minimum occurs at 1545 nm instead of the expected value of 1560 nm, which suggests that the propagation constant is likely to be different from that predicted by simulation. Using the measured coupling ratio as a function of wavelength, as well as the measured excess insertion loss of the MZI devices, $IL = -10\log(T_{12} + T_{14})$, we can update the simulation to estimate the magnitude of the change in $\beta$ necessary to produce these wavelength shifts. Figure 5-11 shows the measured MZI responses superimposed on the simulated responses if we implement a 1.7% reduction in $\beta$ with respect to the original simulation. Considering the earlier discussion of the group delay in nitride rings, the simulated propagation constant may be too high due to an overestimate of the nitride refractive index. In those experiments it was found that a 3% reduction of the index resulted in good agreement with the observed group delay, so a reduced value for the propagation constant here is perhaps expected. As can be seen from the figure, the adjusted simulation agrees well with the measured data; a reduction in $\beta$ may also explain the observed discrepancies in coupling ratios for directional couplers using the BN layer.

For the $\Delta L = 7.29 \mu m$ device, which was the variant included in the laser cavity, the
Figure 5-11: Simulation of MZI responses given $\beta \rightarrow 0.983\beta$, for (a) $\Delta L = 7.18 \mu m$, (b) $\Delta L = 7.29 \mu m$, and (c) $\Delta L = 7.40 \mu m$. Circles denote simulation values, and lines denote the measured responses duplicated from Figure 5-10. The simulation factors in the measured coupling ratio and excess insertion loss as a function of wavelength.

The impact of the wavelength shift on the insertion loss for the signal wavelength is fairly small: the measured loss at 1560 nm was 1.83 dB compared to the minimum value of 1.54 dB at 1545 nm. More concerning is the overall excess loss of the structure, which was about 1.5 dB on average across the wavelength range of interest. When inserted into the laser cavity, this will contribute 3 dB to the round-trip losses, significantly increasing the laser threshold. The most likely cause is loss in the bend waveguides between the couplers, either due to radiation loss or mode mismatch at the junction points. In future design iterations this effect can be mitigated by increasing the bend radius.

## 5.4 Gain Waveguide

Given that the gain waveguide cross-section used for the thulium-doped lasers was designed for pumping at 1600 nm, it is reasonable to expect that the same structure will work well for pumping erbium at 1480 nm. The width of the nitride pieces is 500 nm, and the separation between them is 300 nm. The modes for the pump and signal wavelengths are shown in Figure 5-12. Since the pump and signal wavelengths are relatively close together, we can expect that the modes will be quite similar. The mode overlap in the gain region as a function of the Al$_2$O$_3$ film thickness is shown in Figure 5-13(a), and the small-signal gain for various input pump powers is shown in Figure 5-13(b). For this simulation the erbium concentration was chosen to be $2 \times 10^{20}$ cm$^{-3}$. The confinement factors in each of the constituent materials are summarized in Table 5.1, for a film thickness of 1.1 $\mu$m.

Since the modal gain is determined by the fraction of the mode in the active material, as well as the degree to which the pump mode adequately inverts the population in the area of
signal propagation, the various Sellmeier fits for Al$_2$O$_3$ will all yield similar results. This is because the modal gain will only be affected by the magnitude of the refractive index, and all three fits discussed in Chapter 2 agree very well for this wavelength region. However, the dispersion will of course be significantly dependent on the Sellmeier coefficients. Figure 5-14 shows the waveguide dispersion calculated using each of the three fits summarized in Table 2.1, with the solid line corresponding to the three-pole Sellmeier fit. For the sake of caution, when formulating the dispersion budget we will use the intermediate estimate given by the

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Gamma$(1480nm)</th>
<th>$\Gamma$(1560nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>0.84</td>
<td>0.83</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0.124</td>
<td>0.133</td>
</tr>
<tr>
<td>Air</td>
<td>0.006</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 5.1: Confinement factors in the constituent materials of the gain waveguide, for a 1.1 $\mu$m Al$_2$O$_3$ film.
Figure 5-14: Dispersion of the erbium-doped waveguide. (a) Dispersion for a 1.1 μm film, as a function of wavelength. (b) Dispersion at 1560 nm as a function of film thickness. The dotted line corresponds to ‘Fit 1’, the dashed line corresponds to ‘Fit 2’, and the solid line corresponds to ‘Fit 3’ as denoted in Table 2.1.

dotted line, which is the single-pole Sellmeier curve fitting to all the available data points.

5.4.1 Waveguide Loss Measurement

The motivation behind widening the photonic trench was to reduce the probability of the mode interacting with the trench sidewall, thereby introducing loss. If the primary loss mechanism for the gain waveguide was the sidewall roughness, having a wide trench would eliminate that issue. To characterize the waveguide loss in the wide trench, we included a test structure consisting of the mode-locked laser cavity without reflectors. By measuring the throughput of this structure and calibrating out coupling and nitride spacer waveguide losses, we can estimate the loss in the waveguide by dividing by the length, which in this case is 5.8 cm. This is effectively an average loss throughout the cavity, as multiple transition components are included in the test structure.

Two identical test structures from different wide-trench wafers with a 1.1 μm passive Al₂O₃ film were measured, the results are shown in Figure 5-15(a). The chips were included in the same Al₂O₃ film deposition run, so the properties of the film are identical for both structures. After calibration, we average the results of the two measurements to extract an estimate of the loss, shown in Figure 5-15(b). As can be seen from the figure, this estimate suggests that the loss is not significantly reduced by the widening of the trench. The loss at the pump and signal wavelengths is estimated to be 1.1 dB/cm and 0.95 dB/cm, respectively. The true value will be slightly less than this estimate, given that the transitions are included in the propagation path. There are six trench transitions and gain-waveguide transitions, as
Figure 5-15: Loss characterization of the wide-trench laser cavity at 1550 nm. (a) Measured throughput of two test structures from different wafers, before calibration. (b) Extracted waveguide loss, averaged between the two test structures. The dashed line shows the result after subtracting out the transition losses measured for a 70 \( \mu \)m trench.

well as two Euler bends in the test structure, and these will contribute some loss to the total throughput. As will be discussed in the next section, it is very difficult to lay out cutback-style test structures when using the wide photonic trench, so we were only able to measure the transition components with a 70 \( \mu \)m trench. If we assume that the component losses are similar for both trench widths, then we can subtract out the measured transition losses to get a closer estimate of the gain waveguide loss. The result is shown by the dashed line in Figure 5-15(b). This calculation suggests that the loss peak at 1520 nm is due in large part to the transition components, rather than the gain waveguide itself. This is to be expected from the fact that the confinement factor in the nitride for the trench transition and Euler bend is significantly higher than in the gain waveguide. From this estimate the waveguide loss at the pump and signal wavelengths is calculated to be 0.9 dB/cm and 0.8 dB/cm, respectively.

5.5 Other Laser Components

5.5.1 Transition Components and Euler Bend

For simplicity, we used the same design for the transition components and the compact Euler bend as had been used in the segmented lasers at 1900 nm. Cutback-style test structures for these components are significantly more difficult to lay out properly with the widened trench, due to the fact that the wide trench has a fixed length and is significantly wider than a single cutback test row. The previous method for laying out cutback rows would not
work for this case, since the spacer waveguides would end up under the trench and it would be much more difficult to calibrate them out. Therefore the measurements presented in this section are of components using the 70 µm trench. The insertion loss of the trench transition was measured to be 0.2 dB at the pump wavelength and 0.12 dB at the signal wavelength; the experimental results are shown in Figure 5-16. The performance of the gain waveguide transition is shown in Figure 5-17, with an insertion loss of approximately 0.03 dB across the wavelength band of interest. It is worth noting that due to the nitride absorption peak at 1520nm, the effects of the additional nitride spacer waveguides are particularly pronounced in these measurements. As can be seen from Figure 5-17, for example, the transmission through the gain waveguide transition test rows seems to increase with increasing numbers of transitions. This counter-intuitive result is easily explained by the fact that the loss in the nitride spacer waveguide exceeds the loss through the transitions, such that the total power throughput increases as the length of the spacer waveguide decreases.

The impact of the nitride loss is seen even more clearly in the measurement of the Euler bend, shown in Figure 5-18, with a noticeable increase in loss at the 1520 nm absorption peak. This is expected from the fact that the optical mode is highly confined in the nitride layer for this component. If we compare to the trench transition, which also involves a high degree of confinement in the nitride, we can see that the loss for that component does not decrease at the shorter wavelengths, on the other side of the nitride absorption peak. This is likely because the transition was not optimized for this wavelength range; the width of the BN taper is such that higher-order modes are supported in the later parts of the transition, and the length of the device may not be sufficient at these wavelengths to prevent some small degree of coupling to these modes. This can be easily solved in a later design iteration, although as it is the component does not appear to introduce much loss.

5.5.2 Nonlinear Interferometer and Gratings

The principles of the device design for the nonlinear interferometer and the gratings are the same as described in previous sections, all that is required is to re-simulate the nonlinearity and dispersion at the new center wavelength, and adjust the device parameters accordingly. The design and characterization of the nonlinear interferometer was performed by K. Shtrykova, and is described in [16]. First, the waveguide cross-section was optimized such that the dispersion was minimized while the effective nonlinearity was maximized. This
Figure 5-16: Measured insertion loss of the trench transition in the wavelength range of interest. (Left) Measured throughput for each row, before coupling loss calibration. (Right) Insertion loss per transition obtained with least-squares fit, after calibrating out nitride waveguide losses.

Figure 5-17: Measured insertion loss of the gain waveguide transition. (Left) Measured throughput for each row, before coupling loss calibration. (Right) Insertion loss per transition obtained with least-squares fit, after calibrating out nitride waveguide losses.

Figure 5-18: Measured insertion loss of the compact Euler bend. (Left) Measured throughput for the test structures. (Right) Insertion loss per bend after calibrating out nitride spacer waveguide losses.
resulted in a double-nitride waveguide with a width of 1.0 µm. Several different coupling ratio variations were designed, the components used in the laser cavities were measured to have splitting ratios of 87/13 and 91/9. The loop mirror reflectivity was measured to be approximately 98%. The design and performance of the dispersion-compensating gratings at 1550 nm was discussed in an earlier chapter. For the segmented laser cavities, we used two variants of the FN gratings and four variants of the broadband BN gratings, corresponding to different target GDD values determined by the dispersion budget.

5.6 Dispersion Budget

The dispersion budget is calculated by summing up the individual contributions of each of the constituent components within the cavity, and the target GDD values for the gratings are then chosen to ensure net anomalous dispersion. The gain waveguide dispersion is calculated using the intermediate estimate from the single-pole Sellmeier fit (**Fit 1**). The Euler bend and trench transition GDD values are approximated by calculating the GVD at the cross-section where the BN width is equal to 2.5 µm, and treating the GVD as constant throughout the structure. The Mach-Zehnder and NLI GDD values are calculated from the GVD of their corresponding waveguides, 1.0 µm BN and 1.0 µm DN respectively. The dispersion budget for the segmented laser cavity is shown in Table 5.2; the GDD total for the SBR cavity is given by the first subtotal (without the contribution of the DN waveguide in the NLI) and the total for the NLI cavity is given by the second subtotal. Several laser variations were laid out using different gratings for compensation; the net cavity GDD values are summarized in Table 5.3. Also shown in the table are the estimates when the three-pole Sellmeier fit (**Fit 3**) is used to calculated the gain waveguide dispersion. In all laser cavity variations the net GDD is anomalous, as desired. It should be noted that the grating dispersion values shown in Table 5.3 are the target GDD values, to reflect the decisions made at the time of the chip layout, prior to fabrication and subsequent measurement of those devices. In the case of the FN gratings, the measured devices tended to overshoot the target GDD (i.e. more anomalous), and in the case of the BN gratings the measured devices generally had slightly lower GDD than the targets. It is possible that the last cavity configuration (**NLI**4) therefore has net normal dispersion, depending on the true value of the gain waveguide dispersion.
### Table 5.2: Dispersion budget for segmented laser cavity at 1560 nm. Component lengths are given as round-trip (RT) distances. Abbreviations are as follows: GW – gain waveguide, GWB – gain waveguide bend (Euler bend), TT – trench transition, MZ – Mach-Zehnder (pump/signal combiner), DN wvg – double-nitride waveguide within the nonlinear interferometer.

<table>
<thead>
<tr>
<th>Component</th>
<th>GVD $[\text{fs}^2/\text{mm}]$</th>
<th>RT Length</th>
<th>GDD $[\text{fs}^2]$</th>
<th>Subtotal $[\text{fs}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>60</td>
<td>119 mm</td>
<td>7140</td>
<td></td>
</tr>
<tr>
<td>GWB ($\times2$)</td>
<td>715</td>
<td>1.25 mm</td>
<td>894</td>
<td></td>
</tr>
<tr>
<td>TT ($\times6$)</td>
<td>715</td>
<td>700 $\mu$m</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>MZ</td>
<td>1210</td>
<td>1.15 mm</td>
<td>1392</td>
<td>$1.334 \times 10^4$</td>
</tr>
<tr>
<td>DN wvg</td>
<td>940</td>
<td>20.0 mm</td>
<td>1.88 $\times 10^4$</td>
<td>$3.214 \times 10^4$</td>
</tr>
</tbody>
</table>

The average intracavity power for the erbium mode-locked lasers was simulated using the gain model discussed in Chapter 2, in the same fashion as previously described for the thulium mode-locked lasers. The transition cross-sections and excited-state lifetime of erbium-doped $\text{Al}_2\text{O}_3$ were taken from [19], and the background losses $\alpha_{m,i}$ were estimated from the wide-trench cavity loss measurement. In this case the cavity-averaged loss was used, in order to include the background loss of the transitions. A summary of the parameters used in the simulation is given in Table 5.4. For the NLI, the waveguide loss was assumed to be similar to the 1.0-$\mu$m-wide BN waveguide, and the waveguide length was 9.3 mm. We also include the round-trip insertion loss of the MZI pump/signal combiner, which is estimated to be 3 dB. This component is inserted between the grating reflector and the gain waveguide, and is treated as a lumped-element loss denoted by $c_W$. The results of the simulation for the SBR and NLI laser cavities are shown in Figure 5-19(a). The laser threshold is simulated to be approximately 70 mW and 55 mW for the SBR and NLI lasers, respectively. The NLI cavity is predicted to have a higher intracavity power due to the

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Cavity GDD $[\text{fs}^2]$</th>
<th>Grating GDD $[\text{fs}^2]$</th>
<th>Net GDD $[\text{fs}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBR$_1$</td>
<td>$1.334 \times 10^4$</td>
<td>$7.106 \times 10^4$</td>
<td>$-5.772 \times 10^4$</td>
</tr>
<tr>
<td>SBR$_2$</td>
<td>$1.334 \times 10^4$</td>
<td>$-4.263 \times 10^4$</td>
<td>$-2.929 \times 10^4$</td>
</tr>
<tr>
<td>SBR$_3$</td>
<td>$1.334 \times 10^4$</td>
<td>$-3.359 \times 10^4$</td>
<td>$-2.025 \times 10^4$</td>
</tr>
<tr>
<td>SBR$_4$</td>
<td>$1.334 \times 10^4$</td>
<td>$-2.584 \times 10^4$</td>
<td>$-1.250 \times 10^4$</td>
</tr>
<tr>
<td>NLI$_1$</td>
<td>$3.214 \times 10^4$</td>
<td>$2.56 \times 10^4$</td>
<td>$-7.106 \times 10^4$</td>
</tr>
<tr>
<td>NLI$_2$</td>
<td>$3.214 \times 10^4$</td>
<td>$-4.909 \times 10^4$</td>
<td>$-1.695 \times 10^4$</td>
</tr>
<tr>
<td>NLI$_3$</td>
<td>$3.214 \times 10^4$</td>
<td>$-4.263 \times 10^4$</td>
<td>$-1.049 \times 10^4$</td>
</tr>
<tr>
<td>NLI$_4$</td>
<td>$3.214 \times 10^4$</td>
<td>$-3.359 \times 10^4$</td>
<td>$-1450$</td>
</tr>
</tbody>
</table>

### 5.7 CW Laser Simulations

The average intracavity power for the erbium mode-locked lasers was simulated using the gain model discussed in Chapter 2, in the same fashion as previously described for the thulium mode-locked lasers. The transition cross-sections and excited-state lifetime of erbium-doped $\text{Al}_2\text{O}_3$ were taken from [19], and the background losses $\alpha_{m,i}$ were estimated from the wide-trench cavity loss measurement. In this case the cavity-averaged loss was used, in order to include the background loss of the transitions. A summary of the parameters used in the simulation is given in Table 5.4. For the NLI, the waveguide loss was assumed to be similar to the 1.0-$\mu$m-wide BN waveguide, and the waveguide length was 9.3 mm. We also include the round-trip insertion loss of the MZI pump/signal combiner, which is estimated to be 3 dB. This component is inserted between the grating reflector and the gain waveguide, and is treated as a lumped-element loss denoted by $c_W$. The results of the simulation for the SBR and NLI laser cavities are shown in Figure 5-19(a). The laser threshold is simulated to be approximately 70 mW and 55 mW for the SBR and NLI lasers, respectively. The NLI cavity is predicted to have a higher intracavity power due to the
<table>
<thead>
<tr>
<th>Gain Parameters</th>
<th>Cavity Parameters</th>
<th>Segmented Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{a,p}$</td>
<td>$L_{gain}$</td>
<td>SBR</td>
</tr>
<tr>
<td>$\sigma_{a,s}$</td>
<td>$R_1$</td>
<td>5.8 cm</td>
</tr>
<tr>
<td>$\sigma_e$</td>
<td>$c_W$</td>
<td>0.97</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>$L_{NLI}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$N_l$</td>
<td>$c_{ML}$</td>
<td>9.3 mm</td>
</tr>
<tr>
<td>$\alpha_{m,p}$</td>
<td>$R_2$</td>
<td>0.4</td>
</tr>
<tr>
<td>$\alpha_{m,s}$</td>
<td>1.0</td>
<td>0.639</td>
</tr>
<tr>
<td>2.0 $\times$ 10$^{20}$ cm$^{-3}$</td>
<td>0.95 dB/cm</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 5.4: Parameters used to simulate CW laser operation in the SBR and NLI mode-locked cavities. All parameters listed here are derived from experimental results.

reduced NLI loss compared to the expected SBR coupling losses. Figure 5-19(b) shows how the power evolves in one round-trip of the unfolded laser cavity, with the locations of the reflectors marked by the dotted black boxes. The MZI component is shown at the $z = L$ position, and the mode-locking element at the $z = 2L$ position. These losses are a significant limiting factor for both laser cavities, and future laser designs will focus particularly on eliminating the MZI loss, which should be achievable by increasing the bend radius inside the phase-delay section.

Figure 5-19: CW laser simulation for the erbium-doped NLI and SBR lasers. (a) Simulated intracavity power as a function of input pump power. (b) Intracavity power as it evolves in one round-trip through an ‘unwrapped’ laser cavity, for a pump power of 1W. The grating reflector is positioned at $z = L$ and the mode-locking element is positioned at $z = 2L$, highlighted by the black dashed boxes. Red and blue dashed lines denote the steady-state intracavity laser power.
Chapter 6

Integrated Balanced Optical Cross-Correlator

As mentioned previously, one of the applications for mode-locked lasers as microwave photonic sources is as the master oscillator in a timing distribution system. Mode-locked lasers are especially well-suited for this role due to their low timing jitter characteristics. In order to synchronize remotely located subsystems with precision, an accurate measurement of small timing errors is required. Optical cross-correlation has been demonstrated to be a sensitive technique for measuring the timing jitter between optical pulse trains [11]. The basic principle is as follows: the two pulses whose timing difference is to be measured are combined on a nonlinear element, for example utilizing two-photon absorption or sum-frequency generation, in which the output at the sum frequency is proportional to the product of the incident pulse amplitudes. The maximum output signal will then be generated when the input pulses are perfectly overlapped in time, and thus the cross-correlator provides a feedback signal that can be used to control the pulse timing. However, this simple implementation is vulnerable to amplitude fluctuations on the input pulses, since those fluctuations will be translated into timing errors. Therefore a balanced cross-correlation scheme was introduced, in which amplitude fluctuations are canceled to first order [74].

6.1 Theory and Principle of Operation

An illustration of the balanced cross-correlation technique is shown in Figure 6-1. In this scheme, two pulses whose relative jitter is to be measured are projected onto orthogonal polarizations, and then launched into a nonlinear crystal using type-II phase matching. As the pulses propagate through the crystal, they walk through each other in time, due the
difference in group velocity for the two polarizations. The generated signal at the second harmonic will then be a function of the initial time delay between the pulses as they enter the crystal. A dichroic mirror at the output discriminates the fundamental harmonic (FH) from the second harmonic (SH). The forward SH signal is measured by the first detector of a balanced receiver, and the reflected FH fields travel backwards and generate a new SH signal that will be measured by the second detector of the receiver.

In the balanced configuration, the output voltage from a balanced photodiode will be zero when the input pulses are exactly overlapped, and the error signal will be roughly linearly proportional to the timing difference in the region about the zero crossing. Fluctuations in the pulse timing are then converted to voltage fluctuations, which provide the jitter statistics at high precision, since the balanced scheme by nature suppresses effects of amplitude fluctuations from the measured electrical signal. The proportionality constant is referred to as the sensitivity of the balanced optical cross-correlator (BOC). The higher the sensitivity, the smaller the timing fluctuations that can be detected by the device. The output of the BOC can then be used either to measure the spectral density of timing jitter of a low-noise mode-locked laser, or as an error signal in a feedback loop to control the timing of two lasers with respect to one another [75], or to stabilize the fiber length of a timing distribution link [76]. The key to high-performance systems is therefore to maximize the sensitivity.
of the BOC. We propose to achieve this by using waveguides in a type-II phase-matched nonlinear crystal, periodically-poled potassium titanyl phosphate (PPKTP), to increase the conversion efficiency of the second-harmonic generation process. This will in turn boost the optical output signal incident on the balanced photodiode, increasing the BOC sensitivity. The use of type-II phase-matching is also advantageous for providing a SH signal that is background-free to first order.

6.1.1 Second Harmonic Generation in Waveguides

One of the principal advantages of using waveguides in PPKTP instead of bulk crystals is the increased second-harmonic conversion efficiency. In a waveguide, light at the fundamental frequency can be concentrated into a small area, increasing the intensity, and this small mode size can be maintained over long distances. The result is a dramatic increase in power generated at the second-harmonic, relative to bulk-optics, for the same input power at the fundamental. In order to analyze the behavior of the device and to optimize the design parameters, we developed a model for the key device performance metrics. This allows us to predict the ideal performance of the device and compare to experimentally measured values. In this section we review the theory of second harmonic generation in order to derive an expression for the waveguide SHG conversion efficiency for a continuous-wave (CW) input at a single frequency. First we define the transverse fields in terms of a linear combination of spatial modes in the waveguide:

\[
\vec{E}_t(x, y, z) = \sum_m A_m(x) \vec{E}_{tm}(y, z)e^{-j\beta_m x} \tag{6.1a}
\]

\[
\vec{H}_t(x, y, z) = \sum_m A_m(x) \vec{H}_{tm}(y, z)e^{-j\beta_m x} \tag{6.1b}
\]

where \(A_m\) are the mode amplitudes, \(\beta_m\) are the propagation constants, and the modes are normalized for unity power:

\[
\int \int \frac{1}{2} Re \left\{ \vec{E}_{tm} \times \vec{H}_{tm}^* \right\} dydz = \delta_{mn} \tag{6.2}
\]

The power in each mode is then simply \(|A_m^2|\). Type-II quasi-phase-matched SHG in the waveguide can be modeled using coupled-mode theory as applied to sum-frequency genera-
where subscripts 1 and 2 refer to the FH y-polarized (TE) and z-polarized (TM) modes, and subscript 3 refers to the SH TE mode. The material loss is assumed to be negligible. The phase mismatch parameter is given by: $2\Delta = \beta_3 - (\beta_1 + \beta_2) + 2\pi/\Lambda$, where $\Lambda$ is the poling period for nonlinear domain inversion. The mode coupling coefficients $\kappa_m$ are given by:

$$\kappa_1 = \kappa_2 = (\omega \varepsilon_0 d_{\text{eff}}/2) \iint E_1^* E_2^* E_3 dydz$$

$$\kappa_3 = (\omega \varepsilon_0 d_{\text{eff}}) \iint E_1 E_2^* E_3^* dydz$$

where $\omega$ is the angular FH frequency and $d_{\text{eff}}$ is the effective nonlinear tensor, which for our case can be represented as a scalar, $d_{\text{eff}} = (2/\pi)d_{24}$, since the direction of propagation in the waveguides is oriented along the crystal $x$ axis and the input fields are polarized along the crystal $y$ and $z$ axes. For simplicity, we neglect pump depletion, such that $A_1(x) = A_{10}, A_2(x) = A_{20}$. We then arrive at the SH mode amplitude after integrating Eq. 6.3c over a length $L$ of the crystal:

$$A_3(L) = -j\kappa_3 A_{10} A_{20} L e^{+j\Delta L \text{sinc}(\Delta L)}$$

Assuming equal un-depleted amplitudes for the two fundamental modes, we define the normalized CW conversion efficiency $\eta_0$ in terms of the power generated at the second harmonic:

$$P_{SH} = \eta_0 L^2 P_{FH}^2 \Rightarrow |A_3(L)|^2 = \eta_0 L^2 (|A_{10}|^2 + |A_{20}|^2)^2$$

$$\eta_0 = \kappa^2 \text{sinc}^2(\Delta L)/4$$

where $P_{FH}$ is the total input power at the fundamental frequency, $P_{FH} = P_1 + P_2$, and $\eta_0$ has units of $[\text{W-cm}^{-2}]^{-1}$. 115
6.1.2 Balanced Optical Cross-Correlator

Since the purpose of the balanced cross-correlator is to measure minute time differences between two input pulses, its principle figure of merit is the sensitivity, which we typically report in units of [mV/fs]. If the time difference at the input of the BOC is swept across a range of values, the output voltage will trace out an error curve that crosses zero for the point at which the input pulses are exactly overlapped. The sensitivity is then given by the slope of the voltage curve at this zero-crossing. To develop an analytical expression for the sensitivity, we consider two orthogonally polarized pulses traveling in the waveguide at different group velocities. We neglect dispersive broadening in the crystal (typical sample lengths are on the order of a centimeter) and assume the two input pulses have a Gaussian shape, such that the FH mode amplitudes are given by:

\[ A_1(x, t) = A_{10}e^{-(t-\zeta_1 x - \Delta T/2)^2/\tau^2} \quad (6.7a) \]

\[ A_2(x, t) = A_{20}e^{-(t-\zeta_2 x + \Delta T/2)^2/\tau^2} \quad (6.7b) \]

\[ \zeta_i = \left( v_{g1}^{-1} - v_{g2}^{-1} \right) \quad (6.7c) \]

Here we have shifted to the rest frame of the SH pulse, where \( v_{gi} \) are the FH group velocities and \( \zeta_i \) are the group-velocity mismatch parameters. The pulse-width is given by \( \tau \) and \( \Delta T \) is the time separation between the two FH pulses as they enter the waveguide. To obtain the SH mode amplitude, we substitute Eq. 6.7a and 6.7b into Eq. 6.3c and integrate over a length \( L \) of the waveguide. Assuming perfect phase-matching, we arrive at the expression:

\[ A_3(L, t) = -\frac{j\sqrt{\pi\kappa_3}A_{10}A_{20}}{2c}e^{-(at + b\zeta_2)^2} \left[ \text{erf} \left( cL + \frac{a\Delta T}{2} - bt \right) - \text{erf} \left( \frac{a\Delta T}{2} - bt \right) \right] \quad (6.8a) \]

\[ a^2 = \frac{(\zeta_1 - \zeta_2)^2}{\tau^2(\zeta_1^2 + \zeta_2^2)}, b^2 = \frac{(\zeta_1 + \zeta_2)^2}{\tau^2(\zeta_1^2 + \zeta_2^2)}, c^2 = \frac{(\zeta_1^2 + \zeta_2^2)}{\tau^2} \quad (6.8b) \]

For simplicity, we assume the group velocities of the three modes are very close to one another, such that the mismatch parameters are approximately \( \zeta_1 \approx -\zeta_2 = \zeta \). Then Eq. 6.8a simplifies to:

\[ A_3(L, t) = -\frac{j\sqrt{\pi\kappa_3}A_{10}A_{20}}{\sqrt{8\zeta}}e^{-2t^2/\tau^2} \left[ \text{erf} \left( \frac{2\zeta L + \Delta T}{\sqrt{2}\tau} \right) - \text{erf} \left( \frac{\Delta T}{\sqrt{2}\tau} \right) \right] \quad (6.9) \]
If the two inputs are pulse trains from a mode-locked laser, then the photocurrent generated from this forward pass through the waveguide will be proportional to the power averaged over a single pulse:

\[ J = \alpha f_{\text{rep}} \int_{-\infty}^{\infty} |A_3(L, t)|^2 dt \] (6.10)

where \( \alpha \) is the responsivity of the photodiode and \( f_{\text{rep}} \) is the repetition rate of the mode-locked laser, which is assumed to be the same for both input pulse trains. Similarly, we can obtain the photocurrent generated on the reverse pass and take the difference, such that the output voltage from the balanced detector will be given by:

\[
\Delta V(\Delta T') = \frac{G \alpha f_{\text{rep}} \kappa_3^2 A_{10}^2 A_{20}^2 (\sqrt{\pi} \tau)^3}{16 \zeta^2} \left[ \text{erf} \left( \frac{2\zeta L + \Delta T'}{\sqrt{2\tau}} \right) - \text{erf} \left( \frac{\Delta T'}{\sqrt{2\tau}} \right) \right]^2 \\
- \left[ \text{erf} \left( \frac{\Delta T'}{\sqrt{2\tau}} \right) - \text{erf} \left( \frac{\Delta T' - 2\zeta L}{\sqrt{2\tau}} \right) \right]^2
\] (6.11)

where \( G \) is the trans-impedance gain of the detector, and we have defined \( \Delta T' = (\Delta T + 2\zeta L) \) so that \( \Delta V = 0 \) for \( \Delta T' = 0 \). Finally, taking the slope of the output voltage at \( \Delta T' = 0 \) gives the expression for the sensitivity of the BOC:

\[
K = \frac{G \alpha \kappa_3^2 P_{\text{avg,FH}}^2}{4 \sqrt{2} f_{\text{rep}} \zeta^2} \text{erf} \left( \frac{2\zeta L}{\sqrt{2\tau}} \right) \left[ e^{-\left(2\zeta L/\sqrt{2\tau}\right)^2} - 1 \right] \] (6.12)

where \( P_{\text{avg,FH}} \) is the total average input power at the fundamental, and we have assumed equal mode amplitudes for the two FH modes. For a sufficiently long crystal, such that \( 2\zeta L \gg \sqrt{2\tau} \), Eq. 6.12 simplifies to \( K_0 = G \alpha \eta_0 P_{\text{avg,FH}}^2 / \sqrt{2} f_{\text{rep}} \zeta^2 \), where \( \eta_0 \) is the CW conversion efficiency derived earlier.

6.2 Simulation of Waveguide Conversion Efficiency

In order to calculate the mode profiles in the waveguides, we used a MATLAB implementation of the anisotropic mode-solver described in [78], which is ideally suited for crystals like KTP. The 1-cm-long crystal sample was periodically poled using electric-field-induced domain inversion, the poling period was \( \Lambda = 121.951 \mu\text{m} \), and the sample was poled over its entire length. The waveguides were fabricated by AdvR using Rb$^+$ ion exchange, with the direction of propagation along the crystal x axis. Since the ion diffusion rate along the
KTP z axis is significantly higher than that of the other crystal axes, the waveguides have well-defined edges with respect to the y axis; we approximated the refractive index profile as a step function in this direction. As for the depth profile, for ion-exchanged waveguides this has been shown to be well approximated by the complementary error function [79]. We modeled the index change in the exchanged region as follows, according to typical observed values from AdvR:

\[ \Delta n_i(\lambda) = A_i + B_i\lambda + C_i\lambda^2 + F_i e^{-(\lambda - 350)/G_i} \]  
\[ n_i(\lambda, y, z) = n_{0,i}(\lambda) + \Delta n_i(\lambda) \text{rect}(y/w) \text{erfc}(z/h) \]

where the subscript \( i \) refers to \((y, z)\), \( n_{0,i} \) is the bulk index of KTP, \( A_y = 2.90816 \times 10^{-2} \), \( B_y = -6.5850 \times 10^{-6} \), \( C_y = 2.13894 \times 10^{-9} \), \( F_y = 9.60547 \times 10^{-3} \), \( G_y = 39.20047 \), \( A_z = 2.67947 \times 10^{-2} \), \( B_z = -1.09737 \times 10^{-5} \), \( C_z = 2.29268 \times 10^{-9} \), \( F_z = 2.24565 \times 10^{-2} \), \( G_z = 44.62477 \), and \( \lambda \) has units of millimeters. The width of the waveguides was \( w = 3\mu m \) and the depth parameter was \( h = 5.8\mu m \). There are a large number of Sellmeier fits reported in the literature for the bulk indices of KTP. An extensive investigation of type-II phase-matching for FH wavelengths between 1520 and 1630 nm was carried out in [80], in which a new modified Sellmeier fit for \( n_{0,y} \) was reported. We found that our simulation predicted the measured peak phase-matching wavelength for our waveguides (1560 nm) most accurately when, as is done in [80], we used the equation in [81] for \( n_{0,z} \) and the equation in [80] for \( n_{0,y} \). For \( n_x \) we used the equation reported in [82]. Figure 6-2 shows the resulting electric field profiles of the modes of interest for type-II phase matching, at 1560 nm input wavelength. A visual representation of the waveguide corresponding to the index profile described by Eq. 6.13b can be seen at the bottom right of the figure.

With these field distributions, and using \( d_{24} \approx 3.6 \text{ pm/V} \) [83], we can calculate the expected value of the mode-coupling coefficient, \( \kappa_3 = 0.208 [\text{W-cm}^2]^{-1} \). Assuming perfect quasi-phase-matching for this wavelength, this corresponds to an expected value for the normalized conversion efficiency of \( \eta_0 = 1.08\%/[\text{W-cm}^2] \). Using the calculated mode indices as a function of wavelength, we also find the group-velocity mismatch parameters to be \( \zeta_1 = 81.88\text{fs/mm} \) and \( \zeta_2 = 184.9\text{fs/mm} \). With such a large difference between the two values, the assumption made to obtain the simplified form for Eq. 6.9 will no longer be accurate, and the effective interaction length for the pulses as they propagate in the crystal will be reduced. We can therefore expect the sensitivity for this cross-correlator to be
smaller than that predicted by Eq. 6.12. It is also worth noting that the waveguides support multiple spatial modes at the second harmonic. We might therefore expect for some FH light to be converted into these higher-order modes, which could then interfere with the cross-correlation signal. However, for modes with many spatial oscillations in the field distribution, it is clear that the mode-coupling coefficient $\kappa$ will be very small, and these modes can be safely ignored. Further, although some of the lower-order SH modes have a non-trivial mode overlap with the FH modes, the phase mismatch parameter is dramatically increased, resulting in a vanishingly small conversion efficiency in the wavelength range of interest.
6.3 Experimental Results

6.3.1 Preliminary Waveguide Devices

In the first phases of the project we encountered difficulties with the PPKTP samples that limited our ability to demonstrate a clean cross-correlation trace. Upon further investigation we discovered that the crystals did not have a uniform poling depth across the sample, resulting in an SHG conversion efficiency that was dependent on position along the length of the waveguide, which in turn yielded correlation traces with multiple zero-crossings. Using PPKTP samples that were fabricated with an improved poling process eliminated this problem.

6.3.2 Second Harmonic Conversion Efficiency

On the input facet of the improved waveguides we deposited a coating that was anti-reflective at 1550 ± 50 nm and at 775 ± 25 nm. We then deposited a dichroic coating on the rear facet of the crystal that was highly reflective at 1550 ± 50 nm and anti-reflective at 775 ± 25 nm. Therefore the input FH light was reflected back into the waveguide to generate another SH signal in the reverse direction. An image of the waveguide facet is shown in Figure 6-3a. The KTP chip was then mounted into a fiber-coupled module to provide robust coupling to the waveguides, a photograph of the module is shown in Figure 6-3b. The input fiber was a standard polarization-maintaining fiber whose fast and slow axes were aligned with the principal crystal axes. The forward-generated SH light was collected into a multimode fiber, and the reverse-generated SH light was coupled back into the input fiber.

The experimental setup for measuring the conversion efficiency of the fiber-coupled module is shown in Figure 6-3c. The output of a tunable laser was amplified through an erbium-

![Figure 6-3: (a) Photograph of the PPKTP waveguide facet. (b) Photograph of the fiber-coupled module. (c) Schematic of experimental setup for measuring waveguide conversion efficiency. Abbreviations are as follows: CW – continuous-wave laser, EDFA – erbium-doped fiber amplifier, PC – polarization controller, PD – photodiode.](image)
Figure 6-4: (a) Second harmonic power generated in the waveguide as a function of input power (after coupling calibration). Quadratic fit to the data shown as solid black line. (b) Second harmonic power as a function of input wavelength.

doped fiber amplifier, passed through a fiber polarization controller and a fiber circulator, and coupled into the PPKTP waveguide. The reflected FH light was measured through the return port of the circulator in order to calibrate for the coupling loss between the input fiber and the entrance to the waveguide. The coupling loss was measured to be approximately 3 dB, and the multimode fiber captured approximately 90% of the forward-generated SH light. Figure 6-4a shows the SH power generated at the exit of waveguide as a function of FH power at the entrance to the waveguide, after calibrating out the coupling losses. A quadratic fit to the data shows a normalized conversion efficiency of $\eta_0 = 1.02 \%/\text{[W-cm}^2\text{]}$ for 1560 nm input wavelength. The wavelength dependence is shown in Figure 6-4b. This value for the conversion efficiency agrees well with the result predicted from the simulation, and is well within the uncertainties in the measurement and waveguide fabrication parameters.

6.3.3 Fiber-Coupled Cross-Correlator Performance

Next we investigated the performance of the fiber-coupled modules in balanced cross-correlator operation. Two new PPKTP waveguide chips were fabricated and mounted in fiber-coupled packages. The waveguide parameters for the new chips were similar to the chip described in the previous section, but the poling periods were adjusted slightly in order to have peak phase-matching at 1553 nm, to match the mode-locked laser we used for testing. The experimental setup for characterizing the cross-correlator performance is illustrated in Figure 6-5a. Pulses from the mode-locked laser were split onto orthogonal polarizations and delayed with respect to one another with a motorized delay stage. The pulses were then focused into
Figure 6-5: (a) Diagram of experimental setup for measuring cross-correlation traces with the fiber-coupled BOCs. Abbreviations are as follows: MLL – mode-locked laser, HWP – half-wave plate, QWP – quarter-wave plate, PBS – polarization beam-splitter, COLL – collimator, WDM – wavelength-division multiplexer, BOC – balanced optical cross-correlator, BPD – balanced photodetector, CTRL – controller. (b) Typical balanced cross-correlation trace from fiber-coupled BOC. Detector output voltage recorded as a function of the time delay between the two FH input pulses.

a collimator and into the WDM, which was a custom fiber-coupled dichroic beam-splitter cube; the SH return path was coupled into a multimode fiber and fed to one port of the balanced detector. The output of the detector was then measured as a function of the delay between the input pulses.

Due to the mode mismatch between the input fiber and the SH TE mode, we observed significant excess coupling loss for the reverse-generated SH light, approximately 10 dB less SH light was collected on the reverse path relative to the forward path. To symmetrize the balanced cross-correlation curve, we inserted a 10-dB optical attenuator in the forward path as shown in the diagram. A typical balanced cross-correlation trace for one of the fiber-coupled modules is shown in Figure 6-5b, in which the sensitivity is 9.8 mV/fs. The variability in the output voltage in the regions outside of the zero-crossing is believed to be due to some residual position-dependence of the SH conversion efficiency, similar to the problems encountered with the preliminary waveguide devices that exhibited incomplete poling. However, this effect is relatively small and does not appear to impact the ability of the device to function as a cross-correlator, as the response is linear in the region of the zero-crossing. The total average FH power at the input of the WDM was 7 mW, the repetition rate of the mode-locked laser was 216.67 MHz, and the pulse-width was 172 fs. The balanced photo-detector had a trans-impedance gain of 2 MΩ, a bandwidth of 150 kHz and a responsivity of 0.5 A/W. The WDM had an insertion loss of approximately 1.5 dB.

If we were able to capture all of the reverse SH light, we would immediately gain a factor
of 10 in sensitivity for the device, giving an optimum sensitivity of 98 mV/fs. To estimate the expected value for the sensitivity, we can approximate the group-velocity mismatch parameter as the average of $\zeta_1$ and $\zeta_2$, which gives $\zeta = 134$ fs/mm. From Eq. 6.12, for these operating parameters we should expect to observe a sensitivity of $K_0 \approx 118$ mV/fs, after calibrating out the fiber coupling losses and WDM insertion loss. Due to the large discrepancy between $\zeta_1$ and $\zeta_2$, the effective interaction length in the waveguide will be reduced and therefore the effective group-velocity mismatch will be increased. An increase of 10% in the effective value of the mismatch parameter ($\zeta_{\text{eff}} = 147$ fs/mm) would account for the difference between the measured sensitivity and that predicted by Eq. 6.12.

Using the internal thermoelectric heating element (TEC), we also characterized the temperature dependence of the device sensitivity by measuring the slope of the cross-correlation curve at various TEC settings. The results showed very little dependence on applied temperature around the typical operating point of 25°C, as can be seen in Figure 6-6a, which indicates that the waveguide performance and fiber coupling efficiency is very robust against temperature fluctuations in the environment. As the temperature is increased to 40°C the sensitivities shift slightly, which most likely reflects a small change in the phase matching between the modes in the waveguide. To compare the performance of the new fiber-coupled module against the free-space bulk-optics BOCs that we have used in the past, we measured the sensitivity of each as a function of average FH power at the input to the WDM. Since the current implementation of the fiber-coupled BOC requires the use of the external WDM, they should be considered together as components of the same fiber-coupled module. In [12],

![Figure 6-6: Fiber-coupled BOC sensitivity as a function of (a) temperature and (b) total average FH power at the input of the WDM. Red and blue denote the two fiber-coupled modules, green denotes a typical bulk-optic BOC for comparison.](image)
a conversion efficiency of 0.4% is reported for a laser with 200 fs pulse-width, 200 MHz repetition rate and 15 mW of total average input power. Assuming similar laser parameters and using the effective mismatch parameter discussed earlier, our waveguides would deliver a conversion efficiency of 7.38%, an improvement of a factor of 20 over the bulk-optic result. Due to the SH coupling loss mentioned previously, these fiber-coupled devices were not able to achieve their full potential as expected from the conversion efficiency improvements, but they nonetheless exhibit performance comparable to the bulk-optic version, as can be seen in Figure 6-6b. In order to solve the coupling problem, we next pursued further integration of the WDM coupler onto the KTP chip, with the goal of enabling significantly higher device sensitivities.

6.3.4 Fully-Integrated BOC Module

The primary limitation of the devices described in the previous section was that the input fiber used to couple the FH light into the waveguide was also used to couple the reverse-generated SH light out of the waveguide, resulting in significant coupling losses for the reverse-generated SH signal. The solution to this problem is to separate the reverse-SH and FH coupling paths onto different waveguides, each of which could then have its own optimized fiber for maximum coupling. The simplest way to achieve this is to fabricate a directional coupler on the KTP chip, using the ion-exchanged waveguides. For the short wavelength (SH light), the coupling coefficient will be negligible due to the high degree of confinement within the waveguide. This can be seen intuitively from the simulated mode

![Diagram](image)

Figure 6-7: (a) Schematic of integrated BOC module, including an on-chip wavelength combining coupler to provide a separate output port for the reverse SH path. The red arrows denote the optical path traveled by the FH light, and the green arrows denote the path followed by the SH light. The input is an FC/APC fiber connector, outputs are the photodiode cathode and anode terminals for connection to a TIA circuit. (b) Circuit diagram for connecting the photodiode outputs in a balanced configuration. \( V_b \) is the bias voltage applied to the diodes and \( R_f \) is the feedback resistor that provides electrical gain.
distributions shown in Figure 6-2. Therefore the coupler is primarily designed to couple the FH light from one waveguide into the other, shown schematically in Figure 6-7a.

The fully-integrated waveguide module was fabricated by AdvR; the lateral separation of 127 $\mu$m between the coupler ports was chosen to match that of a standard fiber array. The input facet of the chip was polished at an 8° angle, to match the industry standard for APC fibers. The input fiber array was APC polished and bonded to the input facet. Both SH outputs were collected with multimode fiber, and the input FH port was a polarization-maintaining fiber as before. Similar to the previous module, the output facet of the chip was coated with a dielectric coating designed to be highly reflective for the FH light and anti-reflective for the SH light. The output fibers were then sent to fiber-coupled photodiodes, the electrical outputs of which were then connected to a transimpedance amplifier in a balanced configuration. The circuit diagram for balanced detection is shown in Figure 6-7b, where the feedback resistor $R_f$ determines the transimpedance gain. An image of the packaged module is shown in Figure 6-8.

To characterize its performance, the fully-integrated module was measured with the same cross-correlation delay setup as depicted in Figure 6-5a, and the output leads of the fiber-coupled photodiodes inside the module were connected to the transimpedance amplifier circuit shown in Figure 6-7b, with a feedback resistor of 1 M$\Omega$ and a bias voltage of 5 V. The responsivity of the photodiodes was 0.5 A/W, and the total average input FH power to the module was 10 mW. The resulting balanced cross-correlation trace is shown in Figure 6-9, with a measured sensitivity of 79 mV/fs. For the fiber-coupled module described in the previous section, operating with 10 mW instead of 7 mW average input power and with
1 MΩ transimpedance gain instead of 2 MΩ, we would expect the sensitivity to be 10.0 mV/fs. Therefore the performance of the fully-integrated device represents an eightfold increase in sensitivity compared to the previous generation of BOC devices. The timing resolution of this device is the smallest time shift that can be detected, which will be determined by the noise voltage of the transimpedance amplifier and the sensitivity of the BOC. For a slope of 79 mV/fs, the TIA output noise voltage of 70 μV then corresponds to a timing resolution of approximately 0.89 attoseconds.
Chapter 7

Conclusion

Integrated mode-locked lasers in silicon photonics are poised to become important systems for a variety of applications. The ability to fabricate such devices with CMOS-compatible materials will become increasingly valuable as co-integration with electronics is pursued to increase performance and drive down costs. The mode-locked lasers presented in this work demonstrate great progress toward reliable sources of stable pulse trains on a CMOS-compatible silicon photonics platform, both in the 1550 nm range of interest for telecommunications applications and in the 2 μm wavelength range. The MLLs based at 1900 nm demonstrate Q-switching and Q-switched mode-locking, as well as evidence of stable mode-locking in certain parameter regimes. Many of the constituent components have very broadband performance and can also be used as the basis for MLL designs at 1550 nm. These lasers have a good chance of achieving stable mode-locking operation as well, and can be further improved relatively simply in the next design iteration by updating the design of the pump/signal combiner. Propagation loss in both the gain waveguide and the nitride waveguides used for the mode-locking element continues to be an important focus area for improvement. Understanding and targeting the sources of this propagation loss will help enable a dramatic increase in intracavity power, which makes the design of stable mode-locked lasers much easier. Broadband dispersion-compensating gratings will help enable ultrashort pulse formation, once the remaining uncertainties in the dispersion of various materials are resolved and thoroughly characterized. Devices with 1-dB reflection bandwidths in excess of 70 nm have been demonstrated in this work at 1550 nm, with the characterization limited by the measurement system. The measured dispersion values agree with the design target values to within 10% across several different device designs and multiple chips. Simulation
of devices designed for 1900 nm yields an estimated 1-dB reflection bandwidth of at least 100 nm, pending experimental verification.

In a related application space, balanced optical cross-correlators for the precise measurement of mode-locked laser timing jitter have been designed and implemented in PPKTP waveguides, thereby significantly increasing the conversion efficiency of the second-harmonic generation process. Fiber-coupled modules have been built and characterized, which while suffering from excess coupling loss, nevertheless performed comparably to a bulk-optic implementation. To ameliorate the coupling loss issue, a fully-integrated module using an on-chip wavelength combiner was developed that demonstrated a sensitivity of 79 mV/fs, which constitutes an eightfold increase compared to the previous iterations operating under similar input parameters, and a timing resolution of 0.9 attoseconds. A further increase in sensitivity of approximately a factor of two may be possible according to the model presented in this work. Such devices promise to dramatically reduce the optical power needed to operate a timing-stabilized fiber link, which in turn may enable many more links to be fed from the same master oscillator within a broader timing distribution system.
Bibliography


