# Rare-Earth-Doped Lasers on Silicon Photonics Platforms

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Rare-Earth-Doped Lasers on Silicon Photonics Platforms

A dissertation presented
By
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to
The John A. Paulson School of Engineering and Applied Sciences
in partial fulfillment of the requirements
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Abstract

Laser sources are of great interest due to their wide applications in detection, sensing, communication, material processing and medicine. Silicon photonics is a promising technology which enables these laser devices to be fabricated in a standard complementary-metal-oxide-semiconductor (CMOS) foundry, with the advantages of reliability, compactness, low cost and large-scale production. In addition to the common method of bonding III-V based lasers on silicon photonics platforms, deposition of rare-earth-doped Al₂O₃ glass as gain medium for laser integration has proven to be effective for several key reasons. In this thesis, we present integrated lasers based on rare-earth-doped Al₂O₃ glass, which is deposited on a wafer through a single-step back-end-of-line process. By changing the rare-earth dopant, erbium, thulium, and holmium doped integrated lasers are demonstrated, which provide emission around 1.5 µm, 1.8 µm, and beyond 2.0 µm, respectively.

For the erbium doped laser, a narrow linewidth design and a reliable curved cavity design are included, showing the linewidth of 5 kHz and > 6 times lower lasing threshold compared to straight cavity design, respectively. Additionally, the tunable laser designs utilizing both external fiber gain and integrated Al₂O₃:Er³⁺ gain are demonstrated, showing tuning over the entire C-band. For the thulium doped laser, a
microring cavity design and straight grating based cavity design are included, showing low lasing threshold of 226 μW and high output power of 387 mW, respectively. For the holmium doped laser, a straight grating based cavity design is demonstrated, showing the lasing wavelength beyond 2 μm on a CMOS compatible silicon photonics platform for the first time. In addition, the lasing wavelength shift is demonstrated by changing the Al₂O₃:Ho³⁺ gain film thickness.

Lastly, applications of the lasers in optical communication, beam steering, and optical frequency synthesis are demonstrated. For optical communication, two system level integrations are demonstrated, including cascading grating based lasers to form a WDM light source, and link up a grating-based erbium doped laser with a WDM filter to achieve athermal synchronization. For beam steering, a CMOS-compatible optical phased array powered by a monolithically-integrated erbium laser is demonstrated, achieving one-dimentional beam steering with a 0.85°×0.20° full-width at half-maximum. For optical signal synthesis, the first silicon photonics based frequency synthesizer with a relative frequency instability < 1×10⁻¹⁵ at 100s is demonstrated. The optical frequency synthesizer utilizes a monolithically integrated erbium doped tunable laser locked to the silicon-photonic-based octave spanning optical frequency combs. These results demonstrate integrated rare-earth-doped lasers to be of interest as efficient monolithic light sources for emerging silicon-based photonic Microsystems.
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Fig. 7.8 Cross section of the DFB gain waveguide and double layer Si$_3$N$_4$ MRR. (b) The TE field intensity of the fundamental mode for the DFB gain waveguide and Si$_3$N$_4$ MRR. (c) Refractive index of the materials at 1550 nm. (d) Sketch of the system, including DFB laser cascaded with Si$_3$N$_4$ MRRs (not to scale).  

Fig. 7.9(a) The DFB laser and MRR fabrication steps including (I) deposition and (II) patterning of the bottom Si$_3$N$_4$ layer, (III) deposition and flattening of the SiO$_2$ cladding layer, (IV) deposition and patterning of the top Si$_3$N$_4$ layer, (V) deposition of the top SiO$_2$ cladding layer, (VI) patterning and etching of the top SiO$_2$ cladding to form a laser trench, and (VII) deposition of SiO$_2$ and Al$_2$O$_3$:Er$^{3+}$ within the laser trench. (b) (c) SEM image of Si$_3$N$_4$ pattern (top view) for the DFB laser and MRR after removing SiO$_2$ top cladding from Step III.  

Fig. 7.10(a) External laser measurement setup including a tunable laser to sweep the wavelength of the input signal, polarization controller to ensure the input is coupled.
into the TE mode of the DFB and MRRs, optical powermeter to record the signals from the drop port of the MRRs, and a TEC temperature control to modify, monitor and stabilize the operating temperature of the system. (b) Passive responses of channels 1, 2, 3, and 4 at 20 °C showing matched, low-interfering and adjacent channels. (c) The passive response of channel 1 under different temperatures. A 0.2 nm wavelength shift is observed for a 10 °C temperature change from 20 to 50 °C.

Fig. 7.11 Internal laser measurement setup including a 1480 nm laser pump source together with polarization controller to ensure the fundamental TE mode is coupled into the Al₂O₃:Er³⁺ DFB laser, optical spectrum analyzers I and II to monitor the DFB laser output and MRR drop port signals, respectively, and a temperature control feedback loop to modify and monitor the temperature of the system.

Fig. 7.12(a) (b) Optical spectrum of the DFB output (recorded by OSA I) and channel 1 MRR drop port (recorded by OSA II), under different temperatures. (c) Wavelength shift comparison between the DFB laser and channel 1 MRR. (d) Relative power of the different channels over the temperature range of 20 to 50 °C.

Fig. 8.1(a) Simplified layer schematic of the monolithically-integrated silicon photonics platform utilized for the phased array system (not to scale). (b) Simplified schematic of the phased array system with an on-chip laser showing major components and process layers (not to scale). (c) Photograph of the experimental setup.

Fig. 8.2(a) Diagram illustrating the experimental setup used to characterize the on-chip laser. Measured optical spectrum of the laser showing (b) the full spectrum including the amplified spontaneous emission and (c) the lasing peak at 1599 nm.

Fig. 8.3(a) Measured far field above the chip showing the main lobe of the phased array. (b) Intensity cross sections of the far-field main lobe in the array dimension (green) and the antenna dimension (blue). (c) Experimental results showing beam steering in the array dimension, Y, versus applied electrical power.

Fig. 8.4 The silicon photonic synthesizer circuit with its photonics and electronics arms. The MLL is being stabilized with the help of SC and SHG waveguide (see text for
The color and black arrows represent optical and electronic signals respectively. The vias of the SHG waveguide are to apply reverse bias voltage using metal contact to the P and N doped part of the device. The pump to the CW laser is a 980 nm diode laser. The solid line from the 10MHz reference is to synchronize the respective circuit. The dash line from $f_{ceo}$ lock circuit (ckt) and cw-to-comb lock circuit to the frequency counter is denoting measurement. The synthesized signal is shown in dashed arrow from the CW laser.

Fig. 8.5(a) The SC spectrum with the f, 2f and C-band part shown in yellow band. (b) The measured $f_{ceo}$ signal (inset) and its frequency instability. (c) Frequency deviation of the stabilized CW laser relative to the optical comb frequency to which it is locked. (d) The frequency instability of the CW-to-comb beat note.

Fig. 9.1 The energy level of two close erbium ion, showing the self-pulsing mechanism: energy transfer between two close ions.

Fig. 9.2(a) laser time domain simulation result by solving the rate equation without quenched ion: the laser becomes stable after the 0.01s relaxation oscillation process; (b) laser time domain simulation result by solving the rate equation with quenched ion: the laser has self-pulsing with pulse interval of 100 µs which corresponds to the lifetime of the energy transfer.

Fig. 9.3 An example condition showing how optical feedback affect the laser time domain stability.

Fig. 9.4 Schematic diagram of erbium doped fiber laser. WDM: Wavelength Division Multiplexing; DBR: Distribute Bragg Reflector; EDF: Erbium Doped Fiber.

Fig. 9.5 Stability measurement near the lasing threshold under different doping concentrations (a) Er-16 (b) Er-80 (c) Er-110. As the doping concentration becomes higher, the laser becomes more unstable (d) Er-110 under resonant pumping, the laser becomes stable.

Fig. 9.6 Erbium doped fiber laser setup with feedback.

Fig. 9.7 Stability measurement near the lasing threshold with feedback (a) Er-80, 0 dB
attenuation (b) Er-80, 20 dB attenuation (c) Er-16, 0 dB attenuation

Fig. 9.8 Energy level diagram of two close erbium ions. As pump wavelength is close to signal, the pump photon will stimulate the emission of electrons from upper level, which damps out the oscillations in population inversion.

Fig. 10.1(a) Cross sectional view of the silicon photonic platform showing different layers. TS-Trench (for gain film); FN-first nitride layer; SN-second nitride layer; BN-bottom nitride layer; DN-double nitride layer (first nitride + second nitride); (b) updated Ho laser design with grating reflector in BN layer.

Fig. I.1 Chips and witness sample placed on the substrate holder

Fig. I.2(a) Substrate stage height controller at the bottom of the deposition chamber (b) Control panel of crystal monitor

Fig. I.3(a) Gas and shutter control panel with touch screen (b) CM rotational switch, as marked in red dotted line (c) heater control panel and display

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Chapter 1. Introduction

1.1 Motivation

Silicon photonics is a promising technology for integrated optical circuits [1-3]. The high refractive index contrast between silicon and a silicon dioxide cladding enables compact devices. The current mature silicon production process enables high purity and low defect density silicon material. The compatibility with mature complementary-metal-oxide-semiconductor (CMOS) fabrication technology can lead to low-cost and high-volume production of silicon photonics devices. Thus, silicon photonics technology has enabled production of large-scale devices [4], ultralow power modulators [5], and band-pass filter [6] on a single chip with a low cost and compact size. The strong thermal-optical and electro-optical effects of silicon also enables it to be a good candidate for tunable filter [7] and nonlinear optics [8, 9].

At the same time, with the development of the LASER (Light Amplification by Stimulated Emission of Radiation) technology, long-term benefits have been brought into daily life. Due to the characteristics such as small beam diameter and high energy concentration, lasers are widely applied in industry, including optoelectronic devices fabrication, welding, cutting, drilling, marking, micro-matching, and cleaning. In industry, laser acts as a crucial tool for high precision material processing. Besides industrial applications, laser is also a powerful tool in medical treatment such as eye surgery, skin treatment, and healing. Furthermore, laser is also frequently applied in sensing, metrology and data storage. The specific applications includes telemeters, thermometers, and CD players. In addition, in current high speed, high capacity optical communication, lasers are used as optical signal sources.

However, the silicon material itself, due to its indirect bandgap, is not an efficient gain medium for light emission or lasing. Scientists and engineers have developed different ways to make lasers on silicon substrate, such as bonding III-V laser [10-12], using silicon Raman effect [12], epitaxial growth of semiconductors [13, 14], as well
as co-sputtering rare earth doped $\text{Al}_2\text{O}_3$ glass [15]. Among the different methods to integrate lasers on a silicon photonics platform [11, 12, 14, 16-18], deposition of rare-earth-doped $\text{Al}_2\text{O}_3$ glass as gain medium [18-21] and utilizing complementary metal-oxide-semiconductor (CMOS)-compatible silicon nitride ($\text{Si}_3\text{N}_4$) cavities has proven to be effective for several key reasons. First, $\text{Si}_3\text{N}_4$ has high transparency and low loss from near-IR into the mid-IR wavelength regime and is a mature wafer-scale waveguide platform already applied in passive and nonlinear silicon photonic devices [22-24]. Second, rare-earth-doped $\text{Al}_2\text{O}_3$ glass can be deposited on silicon wafers as a single-step back-end-of-line process [25]. This allows for control of the laser wavelength by changing the thickness of the gain film, which will be discussed in more detail later in the holmium doped laser section. Third, common rare-earth materials such as erbium, thulium or holmium have a wide emission spectrum, enabling a wide tuning range of the laser wavelength [7, 26-30] as well as potential for mode-locking [28-33]. Based on this advantage, we will present erbium tunable laser work in Chapter 3. Fourth, compared to semiconductor lasers, rare-earth-ion-based lasers can provide much narrower laser linewidth because the optical pumping process involves no free carriers [7, 34-36]. We will demonstrate an ultra-narrow-linewidth integrated erbium laser in Chapter 4. Finally, the low thermo-optic coefficient of the host medium ($\text{Al}_2\text{O}_3$) enables laser operation over a wide temperature range by providing good stability without active thermal control [37, 38]. This advantage will be discussed in the athermal synchronization section in Chapter 7.

Within our research group, we have developed the rare-earth-doped $\text{Al}_2\text{O}_3$ thin film deposition capability at the top of wafers fabricated by CMOS foundry (collaborator: CNSE, University of Albany). In this thesis, we are making use of our $\text{Al}_2\text{O}_3$ thin film deposition capability and CMOS wafer fabrication technology to demonstrate lasers with different functionalities on silicon photonics platforms.

**1.2 Objectives for Research**

The objectives of this research work can be separated into the following three points:
The first one is to develop continuous wave (CW) lasers at different wavelength based on different doping materials (erbium, thulium and holmium). The development process includes design, fabrication and characterization of the laser devices. The second one is to develop a tunable laser with wide tunability within communication band. Based on the understanding of the operation and performance of different lasers, the last objective is to apply these lasers at the system level, to achieve athermal synchronization of the laser with a WDM filter, or to cascade erbium doped DFB laser with a tunable phase array to achieve beam steering on a single chip.

1.3 Scope of Project

Most of the work in this thesis is under a team based project Direct On-chip Digital Optical Synthesizer (DODOs) funded by DARPA. Fig. 1.1 shows the schematic of the optical synthesizer proposed by our team. The corresponding block diagram is shown in Fig. 1.2. Within the proposed platform, a high peak power short-pulse generator with a repetition rate locked to the microwave clock is used to seed a silicon based Kerr nonlinear mixer to generate an octave spanning comb. The pulse generator makes use of thulium doped Al₂O₃ thin film deposited within our group as gain medium. Its central wavelength is in 1.9 μm range, and after octave frequency spanning, the supercontinuum covers from 1.2 to 2.4 μm. The long-wavelength end of the comb is then filtered out; the frequency is doubled through second harmonic generation (SHG) process, and then it is locked to the short-wavelength region of the comb to fix the carrier-envelope-offset (CEO) frequency. In this way, it is ensured that the microwave sources represent the only reference in the system. The output is generated by locking a fully integrated erbium doped tunable laser to the comb. The frequencies in between the comb lines are generated using the locked signal coupled to a single-side-band (SSB) modulator.
Fig. 1.1 3D-sketch of the proposed Chip-Scale Electronic-Photonic Synthesizer (CS-EPS).

Fig. 1.2 Block diagram of Chip-Scale Electronic-Photonic Synthesizer architecture
1.4 Organization of the thesis

In this thesis, the following chapters are organized as follow: Chapter 2 introduces the platform of our integrated laser and gain film deposition detail. It is summarized from the deposition experience through my PhD period, including the film thickness control issue, doping concentration control, film thickness uniformity issue, substrate temperature issue, and area selective deposition. The discussions of the laser devices start from Chapter 3, which demonstrates the erbium doped tunable laser using an integrated silicon microring as a tunable filter and erbium doped fiber as external gain. The section includes simulation, design, and characterization of silicon tunable microring and laser cavity. The laser acts as test-bed version of the tunable laser in synthesizer part as mentioned in the previous project scope section. The second part of Chapter 3 discusses a fully integrated erbium doped laser within a silicon photonics platform, using erbium doped Al$_2$O$_3$ thin film as the gain medium, and two silicon nitride tunable rings to form the Vernier effect based cavity. This device is the fully integrated laser source for the synthesizer. The section includes simulation, design, and full characterization of the monolithically integrated tunable laser device. In addition, Chapter 4 also presents two designs of the erbium doped CW laser monolithically integrated on a silicon photonics platform. The first section demonstrates an ultra-narrow linewidth laser (5 kHz), showing one of the advantages of erbium doped laser. The second section demonstrates a reliable integrated laser using curved cavity structure, which compensates the gain film non-uniformity issue within the deposition chamber.

After erbium doped laser, Chapter 5 presents the thulium doped integrated laser. The first section discusses a low lasing threshold, ultra-compact and high efficiency thulium doped laser using ring cavity structure. The chapter demonstrates high efficiency emission capability of thulium doped gain media on our CMOS-compatible silicon photonics platform. Laser design and characterization are included. The second section is on high power distributed feedback (DFB) laser and distributed Bragg
reflector (DBR) laser monolithically integrated on a silicon photonics platform. The gain is provided by Al$_2$O$_3$:Tm$^{3+}$ thin film, and the feedback is provided by silicon nitride Bragg grating. The performance of this device further proves high power emission capability at 1.9 $\mu$m of our thulium doped Al$_2$O$_3$ platform, for the pulse generator under DODoS project, as mentioned in previous project scope section. The section includes the design, simulation, fabrication, and lasing power characterization. Chapter 6 further extends the emission wavelength to beyond 2.0 $\mu$m where thulium emission cross-section diminishes. It demonstrates holmium doped laser monolithically integrated on a silicon photonics platform. Furthermore, it demonstrates lasing wavelength control by changing the film thickness and shows the advantage of back-end-of-line gain film deposition process.

After lasing wavelength control, Chapter 7 talks about system level integration of erbium doped lasers for optical communication. It includes two parts: (1) the first part presents a monolithically integrated WDM light source by cascading DFBs in a silicon photonics platform; (2) the second part demonstrates an athermal synchronization of a DFB laser with a WDM filter due to the similar thermal response of DFB laser and silicon nitride devices. It also shows good thermal stability of the DFB laser contributed by the low thermo-optic coefficient of Al$_2$O$_3$. Further applications of rare-earth-doped integrated lasers are covered in Chapter 8 in two parts: (1) cascade of an erbium doped DFB with a silicon based tunable phase array to demonstrate the chip-scale full integration of light source and phase array; (2) application of erbium doped tunable laser within an optical synthesizer.

Finally, in Chapter 9 the time domain instability issue of rare-earth-doped laser near the lasing threshold is investigated. The potential causes of self-pulsing and how to suppress it are discussed, by using a DBR erbium doped fiber laser as an analogy to integrated laser. Next, in Chapter 10, a conclusion of the entire project is explained and the future work that can be done is explored. Appendix I records the detailed standard operation procedure (SOP) for rare-earth-doped Al$_2$O$_3$ thin film deposition. Appendix II and III are Matlab codes for lasing power calculation based on solving the rate
equation and grating response calculation based on transfer matrix calculation, respectively.
Chapter 2. Al₂O₃ Deposition Process for Integrated Laser

The integrated laser devices developed within our research group are based on rare-earth-doped Al₂O₃ thin film deposited at the top of wafers fabricated by a CMOS foundry. Thus far, laser devices based on this platform have been demonstrated by using different dopant at various wavelengths, including ytterbium at 1.0 µm, erbium at 1.5 µm, thulium at 1.9 µm, and holmium at 2.1 µm. The gain film for laser is deposited at MIT Microsystems Technology Laboratory. Fig. 2.1 shows the deposition machine and the schematic of the deposition chamber. More details about the deposition chamber will be covered in later chapters. In this chapter, several issues about the deposition will be discussed. These issues, which are summarized from deposition experience, include film thickness control, doping concentration control, film thickness uniformity, and substrate temperature control. In addition, the standard operation procedure (SOP) for doing a deposition run is attached in Appendix I of this thesis.

![Deposition machine and schematic](image)

Fig. 2.1 Photo of deposition machine with enlarged schematic of deposition chamber.

2.1 Thin film characterization (witness sample on Metricon)

For each deposition run, we include a witness sample, which has 6 µm thermal silicon dioxide at the top of silicon wafer. In order to measure the film thickness, refractive index and loss of the film deposited, the witness sample is placed on Metricon system
for characterization. The laser signal at 633 nm is normally used. The refractive index of the film at 633 nm is typically 1.66 to 1.67. A good passive film, erbium, or thulium doped active film should have no loss at 633 nm (or low loss beyond the measurement range of the Metricon system). Holmium doped active film has absorption at 633 nm and hence the film is expected to be lossy at 633 nm. Based on the film thickness obtained from 633 nm internal source on Metricon, the film index at 1550 nm can be measured by using the Agilent laser (Agilent 81600B) as the external source. As the Agilent laser can be tuned over C-band, the film index and loss over the C-band can be measured.

2.2 Film thickness control

The film thickness can be controlled by calculating the deposition time based on estimated deposition rate. In order to estimate the deposition rate precisely, a pre-sputter should be done on a quartz crystal microbalance (QCM) monitor. As QCM does not work under high temperature, the pre-sputter should be done at room temperature. The method for deposition rate estimation is to record the bias voltage range (~5 V) on Al target when QCM gives a reading of 0.65 Å/s. This range will correspond to 5.5 nm/min in the real deposition run under high temperature. During the deposition, if the bias voltage is higher or lower than this range, the estimated deposition rate can vary from 4.8 nm/min to 5.9 nm/min.

2.3 Doping concentration control

The doping concentration can be measured by Rutherford Backscattering Spectrometry (RBS). The RBS measurement service is provided by Material Diagnostics, located in University of Albany, NY. The measurement error is ±7%. Table 2.1 (a), (b) and (c) shows the doping concentration level for different target powers of Er, Tm, and Ho, respectively. For the same target power, the doping concentration remains the same for only a limited period of time. It is found that as the dopant target becomes more used, the doping concentration tends to increase. This has more impact on the thulium target,
since it is a frequently used dopant target and it is normally used under relatively high target power (16-18W). Therefore, we recommend a doping concentration calibration for a period of time. For thulium doping concentration, monthly calibration is recommended. For erbium doping concentration, quarterly calibration is recommended. Since holmium target is not frequently used, holmium doping concentration is recommended for annual calibration. In addition, the doping concentration for an erbium-thulium co-doped film has been measured through RBS as well, as shown in Table 2.1(d). Since the deposition machine only has 2 RF power supplies, the third target has to use a DC power supply. For the same target power, the DC power supply gives higher doping concentration compared to RF power supply. The laser devices with this co-doped film at the top have lasing, as reported in a later section of this thesis.
Table 2. RBS measurement data for typical doping target power of (a) erbium (b) thulium (c) holmium (d) Er-Tm codoping.

(a)

<table>
<thead>
<tr>
<th>Sample I.D.</th>
<th>Sublayer 1</th>
<th>Er doping concentration (atoms/cc)</th>
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<td>Density (X $10^{23}$ atoms/cc)</td>
<td>Composition (atomic %)</td>
</tr>
<tr>
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<td>Er</td>
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<tr>
<td>161111 8W Er</td>
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<tr>
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(b)

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<tr>
<td></td>
<td>Tm</td>
<td>Al</td>
</tr>
<tr>
<td>161220 12W Tm</td>
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</tr>
<tr>
<td>161130 14W Tm</td>
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</tr>
<tr>
<td>170226 16W Tm</td>
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<td>0.315</td>
</tr>
<tr>
<td>170215 18W Tm</td>
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(c)

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<td>Density (X $10^{23}$ atoms/cc)</td>
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<td>Ho</td>
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</tr>
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</tr>
<tr>
<td>170324 18W Ho</td>
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<td>0.349</td>
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<td>170329 20W Ho</td>
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<td>0.513</td>
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(d)

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<th>Co-doping concentration (atoms/cc)</th>
</tr>
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<tbody>
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<td></td>
<td>Density (X $10^{23}$ atoms/cc)</td>
<td>Composition (atomic %)</td>
</tr>
<tr>
<td></td>
<td>Er/Tm</td>
<td>Al</td>
</tr>
<tr>
<td>170824(1) 10W Er RF 12W Tm DC</td>
<td>0.9</td>
<td>Er =0.219</td>
</tr>
<tr>
<td></td>
<td>Tm=0.792</td>
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</tr>
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</table>
2.4 Film thickness uniformity issue

The Al$_2$O$_3$ film thickness is measured across the radius of 4-inch diameter circular substrate holder at different points, as shown in Fig. 2.2 below. For thickness of 1000 nm, 12% thickness variation is found across the substrate holder. For a 2-cm long DFB laser, this corresponds to < 10 nm thickness variation. Even for such thickness variation, the cavity response can be highly distorted with significantly reduced Q value, as shown in Fig. 2.3(c) below. More measurement and analysis are included in Chapter 4. To overcome this issue for straight DFB, we propose a compensation scheme based on a curved DFB structure that follows the circular symmetry of the deposition system, as shown in Fig. 2.3(b). In Chapter 4 describing reliable laser, the performance of the curved DFB laser is compared with the straight DFB laser. The curved DFB laser shows 1.2 mW output power with a threshold power of 16 mW, demonstrating >6 times lower threshold compared to the straight DFB laser. More details are included in Chapter 4 and in reference [39].

Fig. 2.2(a) Illustration of the chip position on the substrate holder (b) Thickness variation across the radius of substrate holder.
Fig. 2.3(a) Illustration of straight DFB on the substrate holder; (b) Illustration of curved DFB on the substrate holder, which follows the circular symmetry of the deposition system; (c) The transmission response of straight DFB with no clear 3-dB bandwidth for Q estimation; (d) A symmetric transmission response of curved DFB with measured $Q = 4.55 \times 10^5$.

### 2.5 Substrate temperature issue

On the AJA deposition machine, there is a temperature controller to set the temperature for deposition. An internal thermal couple at the bottom of the stage is in touch with a transparent quartz to monitor the temperature of the quartz. At the same time, it gives feedback to the heater lamps to stabilize it to the setting temperature. From deposition, it is found that there is an offset between the setting temperature and the temperature on the chip substrate. In order to measure the chip substrate temperature, an external thermal couple is kept in touch with the chip substrate, as shown in Fig. 2.4(a). High
temperature silver thermal paste is applied to ensure good thermal conductivity between the external thermal couple and chip substrate. The temperature calibration, as shown in Fig. 2.4(b), provides the measured temperature on chip substrate vs. the setting temperature on the temperature controller. It has been found that for deposition on wafer without metal layer as heater (eg. DDSP1D, DDSP1H), the setting temperature is 550 °C, which corresponds to 415 °C on the wafer substrate. In addition, for deposition on wafer with metal heater (eg. DDSP1E), the setting temperature is 520 °C, which corresponds to 380 °C on the wafer substrate. For deposition on wafer with doped Si heater (eg. Luke, with LER), the setting temperature can be as low as 465 °C, which corresponds to 310 °C on the wafer substrate. Finally, in order to keep the consistency of the deposition temperature on chip, quarterly temperature calibration can be done using the setup shown in Fig. 2.4(a).

Fig. 2.4(a) Chip substrate temperature measurement setup: an external thermal couple is in thermal contact with chip substrate through silver thermal paste; (b) Measured temperature on chip substrate using external thermal couple vs. the setting temperature of deposition machine.

In addition, in order to decrease deposition temperature setting even more and obtain the low-loss lasing film at the same time, a substrate voltage bias can be applied to the chips. The principle can be explained as the following: when the bias voltage is applied on substrate, the ions get accelerated during the process of bombarding the substrate. The kinetic energy of ions is then transferred into the heat on the substrate,
which compensates the reduced heat from substrate temperature setting. The atomic force micrograph (AFM) of the Al₂O₃ film top surface without and with substrate bias are compared in Fig. 2.5 below. For the film deposited without a substrate bias at setting temperature of 250 ºC using Kurt. J. Lesker tool located in the first level of the cleanroom, a root mean square roughness (Rₚ) of 3.34 nm is obtained over a 1 µm² area; and a rough surface morphology is observed. In contrast, when 90 W of substrate bias is used, the surface roughness is reduced by almost an order of magnitude to Rₚ = 0.35 nm, providing a much smoother surface that can help achieve lower propagation losses, as shown in Fig. 2.5(b) below.

![Atomic force micrographs](image)

Fig. 2.5 Atomic force micrographs for films deposited with (a) 0 W and (b) 90 W substrate bias with significant difference in surface texture. Inset shows the profile of a smaller area from the smoother film with the 90 W bias, where the vertical scale is enhanced by 15 times.

### 2.6 Area selective deposition

For the chips with the integrated heater, the metal pads need to be kept open after the deposition. Hence, there is a need to have area selective deposition on the chip. A solution is to use thin glass plate to cover up the area that does not need the Al₂O₃ thin film. Two partially covered chips are shown in Fig. 2.6 below. The metal pads are placed on the left side of the chip during the mask layout process. There is one more chip on the left side of Fig. 2.6 to hold the thin glass plate. Two thick glass plates are placed at the top just to ensure the mechanical stability. This is an effective and simple way to achieve area selective deposition physically. Our group also tried to achieve the area
selection chemically by doing the deposition on the whole chip first, then partially etch away the Al₂O₃ thin film to make the pads open. The problem with the chemical method is the residual photoresist within the trench converts laser to non-working status. Therefore, the physical method is recommended instead of the chemical method. In case that the metal pads are scattering all over the chip instead of located in the same area on the chip, the thin metallic mask can be used to cover the chip to achieve area selective etching.

Fig. 2.6 Two chips (on the right side) within the deposition chamber with metal pads area covered by thin glass plate; one more chip on the left side is used to hold the thin glass plate. Two thick glass plates are placed at the top just to ensure the mechanical stability.
Chapter 3. Erbium-doped Tunable Laser based on Silicon Photonics Platforms

In this chapter we present two versions of erbium doped tunable laser. The first section describes a tunable laser using an integrated silicon microring as a tunable filter and erbium doped fiber as external gain. It acts as a test-bed version of the tunable laser as the light source in synthesizer part, as mentioned in the previous project scope section. Next, the second section presents a fully integrated erbium doped laser on a silicon photonics platform, using erbium doped Al₂O₃ thin film as a gain medium, and two silicon nitride tunable rings to form the Vernier effect based cavity. It is the fully integrated version for the synthesizer.

3.1 Erbium-doped tunable laser using external gain

In order to demonstrate a tunable laser from testbed, erbium doped fiber is used as external gain to construct a tunable laser with integrated Silicon microring as a tunable filter. Compared to lasers using a semiconductor gain medium, lasers based on erbium-doped gain medium have a wide bandwidth across the S, C and L bands. Erbium-doped lasers can achieve a narrow linewidth with large side mode suppression ratios (SMSR) due to homogeneously-broadened gain [36, 40]. Since erbium can be co-sputtered with its hosts (e.g. silica, alumina or phosphate glass), integration into a complementary metal-oxide semiconductor (CMOS) compatible platform is straightforward and the low thermo-optic coefficient of the host media enables operation over a wide temperature range. Erbium-doped waveguide lasers with on-chip cavities have been demonstrated with continuous wave lasing in the C and L bands [20, 35, 41, 42]. However, the lasers were not actively tuned. Laser wavelength can be tuned by perturbing the cavity: A tunable Bragg grating [43], an acoustic optic modulator [44], or an opto very-large-scale integration (VLSI) processor [27] were used to form tunable lasers. These methods were off-chip and hence not applicable for CMOS integrated platforms. Lasers using erbium doped fiber as gain medium with silicon microdisk
cavities have also been demonstrated with passive [45] and active [46] wavelength tunability. However, these demonstrations were not efficient due to losses inside the microdisk cavity. More importantly, the frequency modulated and/or swept-wavelength operation of these lasers using on-chip cavities has not been investigated. Such operation can lead to sources for frequency-modulated continuous-wave laser imaging, light detection and ranging (FMCW-LIDAR) [47] and optical coherence tomography (OCT) at telecom wavelengths [48, 49]. Therefore, a low-loss, high-Q tunable cavity is desired for high swept rate tunable laser sources. Recently, we demonstrated a tunable interior-ridge silicon microring cavity filter with an insertion loss of 0.05 dB and a roughness limited internal Q of $1.5 \times 10^5$ [50]. The silicon microring filter had a 3\( \mu m \) radius and a 35 nm free-spectral-range (FSR) that can be continuously and efficiently tuned (8.1 \( \mu W/\text{GHz} \)) at high speed (fall time $t_f = 2.6$ \( \mu s \), rise time $t_r = 1.6$ \( \mu s \)).

Here, we combine the low loss tunable interior-ridge silicon microring cavity with an erbium-doped fiber to form a swept-wavelength laser. A maximum output power of 2.2 mW with a linewidth of 16±1 kHz is measured and the laser is operated with uniform output power over the C-band from 1530 nm to 1560 nm. When the cavity is rapidly tuned, the swept-wavelength laser response is observed at a mean sweep rate of 22,600 nm/s or 3106 THz/s and a peak rate of 91,300 nm/s or 11605 THz/s.

### 3.1.1 Tunable silicon microring cavity design and characterization

A large uncorrupted FSR was essential for broadband tunability, which required a compact and single mode resonator. For this purpose, we selected an interior ridge silicon resonator, which introduces a hard outer wall. The high index contrast at the outer wall enables tight bend of the waveguide without leaking the mode, as shown in Fig. 3.1. Bend induced loss limited internal quality factors (Q) of an interior ridge resonator and conventional ridge bend waveguides are $10^7$ and $10^3$ respectively for an outer radius of 3.0 \( \mu m \), shown in Fig. 3.2(a). The Q is calculated using the complex propagation constant that is simulated with a finite-difference-cylindrical-eigenmode-solver (FDCEM). The radius of an interior ridge resonator can be further reduced to 2.0
μm while keeping a Q about $1.5 \times 10^5$, which is the line-edge roughness limited Q in our fabrication process. For tunability of this resonator, an embedded silicon heater is formed within the ridge-etched region, using low and high dose p-type implants. The attachment of a silicon heater to the waveguide core directly heats silicon in a thermally isolated environment (i.e. buried SiO$_2$), achieving efficient thermal tuning. This is true if the electrodes that pass current through the heater are isolated from the heater. The low resistance narrow silicon tethers are placed for this purpose. The addition of electrodes within the silicon resonator set the minimum outer radius to 3 μm due to fabrication limitations between the contacts. The FSR of this resonator is 35 nm. The position of the doped regions is optimized for minimum absorption due to the embedded heater. The internal Q was simulated using the FDCEM as a function of doping offset, which is the distance between the outer wall and interior doped region. The simulation result is shown in Fig. 3.2(b). The doping offset that results with an internal Q above $1.5 \times 10^5$ is determined to be above 0.4 μm. The resistance of the heater should be reduced to minimize drive voltage, which is required for CMOS compatibility ($P_h=V^2/R$). Our heater resistance is reduced by forming the heater with multiple resistors that are connected in parallel shown in Fig. 3.2(c). The cavity Q is measured to be $1.5 \times 10^5$. The Q measurement and the fabrication of the cavity are described in [50].
Fig. 3.1 3D-sketch of (a) Conventional ridge ring resonator: showing mode confinement within the ridge waveguide (b) Compact ridge ring resonator: showing leaky mode due to small bending radius (c) Compact interior ridge ring resonator: showing mode confinement within the interior ridge waveguide.
For critical coupling and near perfect reflection, the silicon cavity is placed 150 nm away from the bus waveguides. The through and drop ports of the cavity is measured as a function applied heater power, shown in Fig. 3.2(d). When the heater power of 30 mW is applied, the resonance wavelength of the cavity tuned over the C-band from 1530 nm to 1560 nm, mapped to the gain spectrum of EDF [51].

In addition, the response time of the silicon microring is measured using the setup shown in Fig. 3.3(a) below. Laser at 1530 nm is used to provide probe signal for testing. Polarization controller is used to ensure the probe signal is coupled into the TE mode of the silicon microring waveguide. A square wave electrical modulation is applied to microring, with 5 kHz modulation frequency, 0.15 V peak-to-peak voltage, 0.075 V offset voltage, and 50 % duty cycle. The output signal from dropport of the microcmsg is coupled into a photodetector through an optical fiber. The time response of the output
signal is shown in Fig. 3.3(b). The rising part and falling part is fitted to the following equation (1) and (2) respectively. After curve fitting, the rise time and fall time are obtained as 6.58 µs and 2.40 µs respectively. Since the silicon microring resonance under 0 V is at 1530 nm, the microring heating up time and cooling down time are actually corresponding to the fall time and rise time respectively.

\[ V = a \left( 1 - e^{-t/\tau} \right) + V_0 \]  
\[ V = a \cdot e^{-t/\tau} + V_0 \]

Fig. 3.3(a) Silicon microring switching rate measurement setup; (b) Time domain response of the output signal from silicon microring under 5k Hz square wave modulation.
3.1.2 Widely tunable laser design and characterization

Further, the microring filter is used to form a tunable laser within a fiber loop, shown in Fig. 3.4(a). The loop consists of an erbium doped fiber (EDF), a polarization controller, an output coupler and two wavelength division multiplexers for coupling optical pump in and out of the fiber loop. The fiber loop is supporting a travelling wave, single longitudinal mode, which is commonly used in fiber lasers for ultrashort-pulse generation [52] and observation of solitons [33]. Its unidirectional property is achieved with an isolator. The EDF, with 45 cm length, is single mode (core diameter of 4 μm) and has a doping concentration of $6.6 \times 10^{19}$ ions/cm$^3$ that introduces 110 dB/m absorption at 1530 nm [53]. Fig. 3.4(a) below shows the energy diagram of the erbium ion doped in fiber. The laser is pumped at 980 nm. Under low pump power, the amplified spontaneous emission (ASE) of the EDF is shown in Fig. 3.4(b). The overlap of the EDF gain and microring resonance determines the lasing wavelength. The polarization controller is used to ensure that the light from the fiber is coupled into the TE mode of the microring. A 6.5 μm spot-size lensed fiber is used for coupling optical power to an on-chip inverted Si taper coupler with high efficiency. 10% of the laser power is collected from the output coupler. To measure the loss within the laser system, a 1536 nm laser source is used to probe the laser cavity. The total fiber-to-fiber insertion loss is measured to be around 8.5 dB, which is mainly caused by the coupling loss between the lensed fiber and the on-chip edge-coupler. Based on the loss budget in Fig. 3.4(b), the total loss in the laser cavity in the operational regime is ~12.45 dB, including 11.6 dB internal loss and 0.85 dB external loss. With a given loss budget, the laser output power can be estimated from the lightly coupled laser oscillator model as shown in Eq. (1) [54]

$$P_{out} = \frac{\delta_e}{g} \left( \frac{1}{\delta_e+\delta_o} - 1 \right) P_{sat} \quad (1)$$

where $g$ is the round trip gain, which has a range from 0 to 7. It is the product of the pump power, which is from 0 up to 460 mW, and the unsaturated gain, which is measured to be 0.015/mW. $\delta_o$ and $\delta_e$ are internal and external cavity loss, $P_{sat}$ is the
saturation power of the EDF gain. Based on the laser loss budget, $\delta_e$ is 0.85 dB, corresponding to the loss of the output coupler. $\delta_o$ is chosen to be 11.6 dB, corresponding to measured laser cavity internal loss. The internal loss is reduced to 3.6 dB, corresponding to measured internal loss without fiber-to-chip and chip-to-fiber coupling loss, to observe the effects of on-chip gain media. Based on EDF parameters, $P_{\text{sat}}$ is calculated to be 2.5 mW. The laser output powers under different internal losses are calculated as a function of pump power, shown in Fig. 3.4(c).

Fig. 3.4(a) The erbium-doped fiber laser with the on-chip cavity setup. (b) The loss budget for the laser cavity. (c) Laser efficiency curve based on lightly coupled laser oscillator model.
When the heater inside the cavity is thermo-optically tuned using a DC voltage, the laser operates with relatively uniform output power (<1.5 dB difference) over the C-band from 1530nm-to-1560nm, shown in Fig. 3.5(a). Wavelength tuning of up to 30 nm in 5 nm step is observed with corresponding heater powers of up to 30 mW in 5 mW steps. These values correspond to a heater efficiency of 1 mW/nm (~8.1 μW/GHz). The SMSR is found to be larger than 45 dB. The laser efficiency curve at 0 V DC. bias to the tunable microring is shown in Fig. 3.5(b). The laser output power is observed up to 2.2 mW via an external power splitter. The slope of experimental result matches with the slope of simulation result in Fig. 3.4(c), for an internal loss of 11.6 dB. The deviation of power measurement points from linear curve can be contributed by the nonlinear absorption within the silicon microring cavity. Due to the intensity enhancement inside the microring cavity, the nonlinear absorption of silicon will ultimately constrain of the maximum output power of our laser device.
3.1.3 Swept-wavelength (frequency modulated) operation and linewidth measurement

In order to measure the sweep rate of the tunable laser, a separate passive microring resonator is used as a frequency reference. The schematic of the setup is shown in Fig. 3.7(a). First, electrical modulation is applied on the tunable microring filter within the laser cavity. The electrical modulation signal is a sinusoid, with 2.10 V peak to peak and a 2.77 V DC offset. The frequency is first set to 100 Hz. The output spectrum of the tunable laser is shown in Fig. 3.7(b) under a maximum hold on an optical spectrum analyzer. It shows that our tunable laser under such modulation spans a 10 nm wide range, from 1532 to 1542 nm. This wavelength range is selected to maintain linearity of the wavelength tuning with a sinusoidal heater voltage. For a wider wavelength range, the drive signal needs to be engineered to maintain linearity. Then the laser output is injected into the passive microring resonator, with 2.1 nm FSR as shown in Fig. 3.7(c). As the tunable laser wavelength passes the resonant wavelength of reference microring resonator, the output signal recorded by the oscilloscope reveals a dip in transmission, as shown in Fig. 3.7(d). The 5 ms time span in Figs. 3.7 (d) and (e) covers half of the electrical modulation period. Within this time duration, the tunable laser sweeps from 1532 nm to 1542 nm and then goes back to 1532 nm, passing through the
resonances of reference microring resonator twice. In Fig. 3.7(c), the wavelength difference between 1\textsuperscript{st} and 4\textsuperscript{th} resonance is $\Delta \lambda = 6.45$ nm, and in Fig. 3.7(d) the time difference between 1\textsuperscript{st} and 8\textsuperscript{th} dip is $\Delta t = 4.52$ ms. Therefore, the mean sweeping rate of our tunable laser can be calculated to be $2\Delta \lambda / \Delta t = 2854$ nm/s, corresponding to 362.35 THz/s. Fig. 3.7(e) plots the swept wavelength with respect to time. By taking the maximum slope of the polynomial fitting curve, the peak sweeping rate is calculated to be 4290 nm/s, corresponding to 545.44 THz/s. In order to determine the maximum sweeping rate, the modulation frequency is further increased up to 800 Hz. This value is chosen because nonlinearities are observed above this frequency. The results for this case are shown in Fig. 3.7(f)-(g). The mean and peak sweeping rates are measured to be 22,600 nm/s (3061 THz/s) and 91,300 nm/s (11605 THz/s) respectively. The swept-rate is ultimately limited by the relaxation oscillation within the erbium doped fiber [55]. The rate can be increased if the oscillation between switched wavelengths can be controlled with an electrical feedback-loop [56] or a nonlinear loop mirror with a gain equalizing filter [57].
Fig. 3.7(a) Sweep rate measurement setup (b) The measured swept-wavelength response with an optical spectrum analyzer using maximum hold setting to show wavelength tuning range. (c) The passive spectrum of the reference SiN resonator with 2.1 nm free-spectral-range. (d)/(f) Time domain signal after the microring resonator at 100 Hz and 800 Hz modulation frequency. (e)/(g) Swept wavelength with respect to time at 100 Hz and 800 Hz modulation frequency.

The settling time of the tunable laser is also measured during the wavelength tuning
process. An electrical power is applied to silicon microring to tune the wavelength until the signal becomes table in time domain. The time domain signal in oscilloscope is shown in Fig. 3.8 below. Laser relaxation oscillation process is observed here. 1 ms settling time is obtained for this tunable laser with external fiber gain and a total cavity length of 4 m. For fully integrated tunable laser with much shorter cavity length, the expected settling time is much shorter, in the scale of 10s of μs.

![Figure 3.8](image)

**Fig. 3.8** Time domain signal as laser wavelength is tuned, showing 1 ms laser settling time.

In general, the laser linewidth is defined as the full width half maximum (FWHM) of its emission spectrum at the lasing wavelength. It is a representation of the noise level of the laser. Its source can be classified into two kinds: the quantum noise and technical noise [58-60]. The quantum noise comes from the spontaneous emission, and hence it is the fundamental limit of the laser linewidth. It can be calculated from the Schawlow-Townes formula, as shown below:

\[
\Delta \nu_L = \frac{2\pi h \nu_L (\Delta \nu_c)^2}{P_{out}}
\]

where \( h \) is Planck’s constant, \( \Delta \nu_L \) is the laser linewidth, \( P_{out} \) is the output power of the laser, and \( \Delta \nu_c \) is the passive cavity linewidth, which is related to the cavity lifetime \( \tau_c \). For the three-level laser system, in order to account for reabsorption loss and intrinsic cavity loss, the generalized Schawlow-Townes formula [61] can be used, as shown below:
$$\Delta \nu_L = \frac{2\pi h\nu_L (\Delta \nu_c)}{P_{out}} \left[ 1 - \frac{\tau_c}{\tau_{loss}} \right] \left[ 1 - \frac{\sigma_L^{abs}(ct, \sigma_L^{em} N_T-1)}{\sigma_L^{em}(ct, \sigma_L^{abs} N_T+1)} \right]^{-1}$$

(3)

$$\frac{1}{\tau_c} = \frac{1}{\tau_{loss}} + \frac{1}{\tau_{out}} = 2\pi \Delta \nu_c$$

(4)

where $c$ is speed of light, $N_T$ is the doping concentration of the active gain media, $\sigma_L^{abs}$ and $\sigma_L^{em}$ are the absorption and emission crosssection, respectively. Due to the additional reabsorption loss within the laser cavity, the generalized Schawlow-Townes limit shows significant linewidth broadening [62]. The cavity lifetime $\tau_c$ is determined by the waveguide loss decay lifetime $\tau_{loss}$ and mirror loss lifetime $\tau_{out}$. Based on the equations above, the laser linewidth can be reduced by higher cavity Q with lower reabsorption loss. In the meanwhile, the source of technical noise mentioned before is from environment, such as mechanical vibrations, temperature fluctuations, and pump power fluctuations. In order to get lower technical noise and hence narrower laser linewidth, the fluctuation of environment should also be minimized.

In order to measure the linewidth (< 1MHz) of the Er tunable laser, the delayed self-heterodyne detection method [63] is used. The setup is shown in Fig. 3.9(a). The laser signal at 1530 nm (0 voltage applied to microring) is split into two by the 3dB coupler on the left side. One signal goes through polarization controller 1 (PC 1), and the other signal goes through a delay line. Here the delay line is constructed in a circulating loop as shown in the lower loop of the measurement setup. An acousto-optic modulator (AOM) provides a frequency shift of 44 MHz. Since our Er laser has narrow linewidth, a fiber delay of 35 km is used, and as the circulation number $N$ increases, the total delay length increases. This circulating structure ensures there are higher order harmonics which are incoherent with the signal propagating through PC1. While the circulating number $N$ increases, the SNR in the loop decreases. Hence, an erbium doped fiber amplifier (EDFA) is used to compensate the loss of the circulating loop and maintain the SNR. A tunable filter is tuned to signal wavelength to suppress the amplified spontaneous emission of EDFA. The beating process is illustrated in Fig. 3.9(b). The beating in time domain corresponds to an autocorrelation process in frequency domain. If the original linewidth of the laser is $\Delta f$, after self-heterodyne
interferometer, the beating signal will have a FWHM of $2\Delta f$, as a result of autocorrelation in frequency domain. Hence, the linewidth is obtained by dividing the FWHM of beating signal by 2. A series of beating signals are detected by an electrical signal analyzer (ESA) and are shown in Fig. 3.9(c). This spectrum contains harmonics from the 1st to 20th orders. The measured linewidth of each harmonic, as illustrated in Fig. 3.9(d), has an increasing trend. The linewidth reaches a stable value when the harmonic number is larger than 15. A stable and narrow linewidth of 16±1kHz is observed with no coherence artifacts after a delay length of 350 km (>10th harmonic). The 18th harmonic ($f=18\times44$ MHz=792 MHz) electrical response and the Lorentzian fitting are shown in Fig. 3.9(e). Such a laser linewidth corresponds to a coherence length of 13 km, which is significantly shorter than the total 350 km fiber delay length. This verifies that the delay length used here is long enough to ensure incoherence.
Fig. 3.9 (a) Linewidth measurement setup: loss-compensated circulating delayed self-heterodyne detection (b) Beating process in frequency domain is autocorrelation process (c) The beating signal of 20 harmonics (d) Linewidth measurement for different harmonics (e) Self-heterodyne spectrum with Lorentzian fitting showing a combined linewidth of 16 kHz.
3.1.4 Summary

In this section, we demonstrated an erbium-doped fiber laser with a tunable interior-ridge Si microring cavity. Laser tunability is achieved by thermally tuning the microring filter. The filter demonstrated has Q factor $1.5 \times 10^5$, insertion loss $<0.05$ dB, and tuning efficiency $8.1 \, \mu$W/GHz. Continuous wavelength tuning is achieved over a wide wavelength range (C-band) with output powers up to 2.2 mW. The laser with narrow linewidth (16 kHz) and high speed swept-wavelength operation (91,300 nm/s) represents a promising uncooled FMCW-LIDAR or OCT source.

3.2 Fully integrated erbium-doped tunable laser

In an integrated photonic circuit, a tunable laser source is a key component for a variety of applications, including spectroscopic measurements [64, 65], wavelength division multiplexing (WDM) [66, 67], frequency-modulated light detection & ranging (LIDAR) [47], optical coherence tomography (OCT) [49, 68], and grating-based beam steering [69]. Wide tunability is commonly obtained by utilizing a Vernier effect based on two cavities with slightly different free-spectral ranges (FSRs) [70-72]. The Vernier effect has been shown using Bragg grating reflectors or ring resonators [70-74], with ring resonators being commonly used for wide wavelength tuning purposes.

Since erbium can be co-sputtered with its hosts (e.g. silica, alumina or phosphate glass) [75-77], integration into a CMOS-compatible silicon photonics platform is straightforward as a back-end step. Monolithically integrated erbium-doped waveguide lasers have been demonstrated with both continuous-wave and pulsed lasing using erbium co-sputtered with Al$_2$O$_3$ as a host [18, 20, 25, 32, 35, 78]. The low thermo-optic coefficient of Al$_2$O$_3$ enables robust operation of the laser over a wide temperature range [37, 79], important for control-free WDM systems [38]. However, previously demonstrated lasers could not be actively tuned. Lasers using erbium-doped fiber as gain media with integrated silicon microdisk cavities have been demonstrated with passive [45] and active [7, 46] wavelength tuning (including the one presented in
previous section). However, these demonstrations were not compact since they are mostly fiber based and not fully integrated on-chip.

In this section, we present the first monolithically integrated erbium-doped laser on a CMOS-compatible silicon photonics platform. The crosssection of the platform is shown in Fig. 3.10 below. Wavelength tunability is achieved by utilizing a Vernier structure, which is formed by two Si$_3$N$_4$ micro-ring resonators. Erbium-doped Al$_2$O$_3$ is deposited as a back-end step and used as the gain medium; and metal layers are deposited as heaters and contacts. Wavelength tuning over 46 nm (from 1527 to 1573 nm) with more than 40 dB SMSR is achieved. With 100 mW on-chip 980 nm pump power, up to 1.6 mW output lasing power is obtained, with a 2.2% slope efficiency. The fine-tuning capability of the lasing wavelength is demonstrated by tuning a separate heater in the gain cavity that shifts the longitudinal cavity modes. The signal/heater response time is measured to be around 200 µs and 35 µs for coarse and fine tuning, respectively. In addition, the laser linewidth is measured to be 340 kHz by using a self-delay heterodyne method. Furthermore, the laser signal is stabilized by continuous locking to a mode-locked laser (MLL) over 4900 seconds. The control signal is feedback to the heater for longitudinal-mode phase shifter. The peak-to-peak frequency deviation of the signal remains to be <10 Hz.

![Layer Information](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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<tr>
<td>SNP</td>
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</tr>
<tr>
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<td>1$^{st}$ SiN</td>
</tr>
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<td>ZNP</td>
<td>Bottom SiN</td>
</tr>
<tr>
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<tr>
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<td>EVP</td>
<td>Heater Via</td>
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<tr>
<td>MLP</td>
<td>Wirebond Pad</td>
</tr>
<tr>
<td>TSP</td>
<td>Trench</td>
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</tbody>
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Fig. 3.10 The silicon photonics platform crosssection for integrated tunable laser
3.2.1 Integrated tunable laser design

A schematic perspective view of the tunable laser design is shown in Fig. 3.11(a), which includes all the layers used in the silicon photonics platform. It has a compact footprint of 0.23 cm² (1 mm × 2.3 cm). Fig. 3.11(a) includes the zoom-in view of the wavelength tuning components, which consists of two micro-ring filters in a Vernier configuration and a gain-cavity longitudinal-mode phase shifter with metal heater layer at the top. The rings are made of 200 nm thick and 1.6 µm wide Si$_3$N$_4$ with a radius of 100 µm and 104.6 µm, thereby giving a free spectral range (FSR) of 2.23 nm and 2.13 nm respectively, and combined FSR of 50 nm for wide tuning within erbium gain bandwidth. The coupling gap is designed to be 563 nm resulting in 8.75% calculated power coupling for the signal wavelength while no 980 nm pump light couples. This is due to the large confinement of the pump in the Si$_3$N$_4$ bus waveguide, thereby obtaining a low-loss pump/signal combiner inside the laser cavity. Power coupling more than 8.75% leads to wider bandwidth for each resonance of the micro-rings in, and hence side mode extinction will be lower for the laser. In contrast, power coupling lower than the optimized value leads to more energy trapped in micro-ring, and, hence, the intrinsic loss of the ring will dominate. Therefore, the 8.75% power coupling is chosen to balance between the side-mode extinction and intrinsic loss of the ring during the laser design.

The length of each gain-cavity longitudinal-mode phase shifter is 500 µm and 2π phase shift can be readily achieved. Both gain cavity phase shifters and rings can be thermally tuned separately using a TiN/Al alloy metal layer above the waveguide. The heater layer has a width of 5 µm, and is located 2 µm above the Si$_3$N$_4$ layer to ensure optical isolation, as shown in Fig. 3.12 below. The resistivity of the heater metal alloy is designed for 15 Ω/sq. Due to the low thermo-optic coefficient of Si$_3$N$_4$, a simulated 2π phase shift requires at least 370mW of electrical power. The thermal profile is shown in Fig. 3.12(d) below and the heater reaches a maximum temperature of 600 °C. The heater layer is connected to the contact pads through vias. Both contact pads and vias form the M1 layer, which is made of a low resistance TiN/Al alloy for electrical routing.
The optical mode in the Si$_3$N$_4$ layer is coupled to the laser gain waveguide through an adiabatic transition. The transition loss is measured to be 0.3 dB/transition. The gain waveguide is formed by a 1.1 µm thick Al$_2$O$_3$:Er$^{3+}$ film deposited within a 4 µm deep and 5 µm wide trench. The green color fluorescence due to the up-conversion in Er$^{3+}$ under 980 nm pump is shown in Fig. 3.11(b). The electrical probe is in contact with the fabricated device for thermal tuning. Fig. 3.11(c) shows a scanning electron microscopy (SEM) image of the gain waveguide cross-section. The depth of the trench is accurately controlled using the top Si$_3$N$_4$ layer as an etch stop, as illustrated in Fig. 3.11(c) below. For the gain waveguide, the mode confinement factor within the Al$_2$O$_3$:Er$^{3+}$ layer for the pump (980 nm) and signal (1550 nm) fundamental TE modes are calculated to be 90% and 80% respectively using 2-D Eigen mode solver. The refractive indices used in the mode calculation are listed in Fig. 3.11(d). The gain waveguide is bent to allow for a >4 cm long waveguide to provide sufficient gain. Fig. 3.11(e) shows the mode profile at signal wavelength for several bending radii. The large bend mode mismatch between these modes is resolved by using an adiabatic Euler bend [80] which was simulated to be lossless with a minimum bending radius of 200 µm. From cutback test measurements (cutting back the number of bends), the Euler bend loss is estimated to be 0.6 dB per a 180 degree bend.

The simulated response of two combined Si$_3$N$_4$ rings is shown in Fig. 3.13(a), which provides an FSR of 50 nm. Fig. 3.13(b) shows the simulation results of the combined ring filter response together with the laser cavity response. The simulated laser cavity longitudinal-mode spacing is 2.5 GHz, for a round trip cavity length of 4.6 cm. The selected lasing mode has 1.8 dB selectivity over the closest side mode.
Fig. 3.11 (a) 3D illustration of an integrated tunable laser, showing different material layers, heaters for microring and gain cavity phase shifters (not to scale). (b) Fabricated device on the test setup, showing erbium green color fluorescence under 980 nm pump. (c) SEM image of the tunable laser gain waveguide cross section. (d) Refractive indices of the waveguide materials at both pump and signal wavelengths. (e) The transverse electric (TE) field intensity of the fundamental mode at signal wavelength for different bend radii along the Euler bend.
Fig. 3.12 (a) Schematic cross section of the heater above the Si$_3$N$_4$ waveguide; (b) Simulated phase response of heater as a function of electrical power; (c) Simulated thermal profile.

Fig. 3.13 Simulated transmission spectrum of (a) the combined Vernier ring response and (b) the combined Vernier ring response (curve in blue) overlap with the gain cavity longitudinal mode (curve in orange).

The device is fabricated on a 300 mm silicon wafer with a 6 µm buried oxide. The fabrication process of the Si$_3$N$_4$ layer and laser trench is the same as reported before.
An 1100-nm-thick Al$_2$O$_3$:Er$^{3+}$ thin film is deposited via reactive co-sputtering. The deposition of Al$_2$O$_3$:Er$^{3+}$ film is a single-step back-end-of-line process on the silicon wafer, allowing direct access to the laser design [82]. More detail of this reactive co-sputtering process is reported earlier [82, 83] with difference on dopant. The substrate temperature of the deposition was measured to be 380°C. The background loss of Al$_2$O$_3$:Er$^{3+}$ film was measured to be <0.1 dB/cm. Deposition runs with different doping levels reveal an optimum Er$^{3+}$ doping concentration of $1.5 \times 10^{20}$ cm$^{-3}$. Given the same pump power, a lower doping concentration will suffer from lower gain while a higher concentration will result in ion clustering and quenching [84, 85].

### 3.2.2 Wavelength tuning and further characterization

First, we obtained the spontaneous emission spectra of erbium-doped Al$_2$O$_3$ films, which emit near 1.55 µm (C-band). We deposited Al$_2$O$_3$:Er$^{3+}$ film on top of the SiO$_2$ layer. A low power pump at 980 nm (at the Er$^{3+}$ absorption peak) was used to generate spontaneous emission in the Al$_2$O$_3$:Er$^{3+}$ film. The spectrum recorded by an optical spectrum analyzer is shown in Fig. 3.14(a). It shows that the emission range is from 1524 nm up to 1574 nm, with 3-dB bandwidth of 50 nm. To demonstrate the wide tuning capability within this emission range, both ring heaters are tuned using DC voltages. Lasing wavelength tuning over the C-band from 1527 nm to 1573 nm is shown in Fig. 3.14(b), with relatively uniform output power (<1.5 dB difference). Wavelength tuning up to 46 nm with more than 40 dB SMSR is achieved. Lasing at 1525 nm is also observed, but with less than 40 dB SMSR due to diminished gain of the erbium ions. Fig. 3.14(c) shows the laser cavity resonance wavelength tuning by heating two microrings simultaneously. For a given heating power P2 on ring 2, as the power P1 increases, the ring 1 resonance shifts, and, hence, the laser cavity resonance wavelength jumps to the next ring interference for two ring resonance peak matching. For a specific lasing wavelength setting, the heating power of both rings should be
adjusted so that the ring 1 resonance peak matches with one of the ring 2 resonance peaks at the desired wavelength.

Laser devices with two different gain waveguide lengths (4.2 cm and 8.4 cm) are fabricated. The device with an 8.4 cm long gain waveguide is chosen for the following efficiency and power measurement as it gives relatively better performance. The laser power efficiency curve as a function of pump power at 1561 nm is shown in Fig. 3.14(d). The pump input port and lasing signal output port are marked in the laser schematic as shown in Fig. 3.11(a). Lasing power up to 1.6 mW is collected from the output port on-chip when 107 mW of on-chip power at 980 nm is used for pumping. A slope efficiency of 2.2% with respect to on-chip pump power at 980 nm is obtained.

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Fig. 3.14(a) Wide C-band spontaneous emission of Al₂O₃:Er³⁺ film covering from 1524 nm to 1574 nm, pumped by a low power 980 nm pump source; (b) Laser output spectra showing 46 nm
tuning range from 1527 nm to 1573 nm, with >40 dB SMSR; (c) Laser cavity resonance wavelength tuning for difference heating powers applied on the heaters for both ring 1 and ring 2; (d) On-chip laser output power with respect to launched on-chip pump power, showing 2.2% slope efficiency and 1.6 mW maximum signal power achieved.

To characterize the fine-tuning capability of the Er integrated tunable laser, a reference laser at a fixed wavelength is used to beat with the tunable laser through an optical combiner, as shown in Fig. 3.15(a). The beat signal was detected by a photodetector (PD) (EOT ET-3500F), and recorded by an electrical signal analyzer (ESA) (Advantest U3741). The gain cavity phase shifter, as shown in Fig. 3.11(a), is used for the fine tuning, as the FSR of the cavity (~2.5 GHz, for a round trip cavity length of 4.6 cm including the 4.2 cm gain waveguide) is much smaller than the FSR of the Si$_3$N$_4$ ring (~250 GHz). The beat frequency under different electrical powers supplied to the gain cavity phase shifter are shown in Fig. 3.15(b). As we increase the electrical power, the beat signal shifts continuously to higher frequencies, without mode hopping. Fig. 3.15(b) shows the fine tuning over 2.5 GHz, with up to 170 mW electrical power delivery. The tuning efficiency can be obtained as 14 MHz/mW by fitting the data points to a linear curve.

Fig. 3.15(a) Fine tuning measurement setup: the tunable laser signal and a signal at a fixed wavelength are beat through a combiner. Beat signal is detected by PD. (b) The beat frequency with respect to electrical power applied on gain cavity phase shifter, showing continuous fine tuning.
The time domain of the laser signal is detected by a PD and monitored by an oscilloscope, as illustrated in Fig. 3.16(a). Strong dependence of time domain stability on pump power is observed. Under the condition that pump power is slightly above lasing threshold, the tunable laser device demonstrate self-pulsing behavior with a frequency of 0.125 MHz, as shown in Fig. 3.16(a) red curve. This can be explained by the ion-pair formation in the gain medium [86, 87]. As the pump power is increased to beyond lasing threshold (>2 times higher than threshold), the relaxation oscillation frequency is increased and the pulsing behavior is suppressed, as shown in Fig. 3. 16(a) green curve. This is due to the fact that higher pump power causes population inversion and gain to be replenished rapidly [87, 88]. The small output fluctuations may contributed by the noise from PD, pump diode and mechanical vibration of fiber. More details about self-pulsing will be discussed in Chapter 9 of this thesis.

With the aim of measuring how fast the laser cavity responds to the electrical power applied on the heaters, a square wave with a 50% duty cycle is used to modulate the heaters for the microring and the gain cavity phase shifter. These two heaters are used for coarse tuning and fine tuning of the laser signal, as demonstrated in the previous two sections. The electrical resistance of the heaters for the microring and gain cavity phase shifter are measured to be 240 Ω and 25 Ω, respectively. The differences in resistivity are contributed by different heater lengths and wirings. The laser output power is detected by an external photodetector. The time response of the modulation is captured by an oscilloscope, as illustrated in Fig. 3.16(b) and (c) below. Fig. 3.16(b) shows the response of the laser as one microring is modulated by a square wave signal with 200 Hz frequency. The rising curve and falling curve are fitted by an exponential function as shown in equation (1) and (2) below, respectively. The rise and fall time are obtained from the fitting parameter τ, which is 200 µs and 230 µs, respectively. Fig. 3.16(c) shows the response of the laser signal as the gain cavity phase shifter is modulated by a square wave signal with 2.5 kHz frequency. After curve fitting, the ride and fall times are obtained as 32 µs and 37 µs, respectively. Compared to the microring heater, the heater for the gain cavity phase shifter has a different response time due to
the differences in thermal conductivity of the components. Furthermore, time-domain
instability issue due to self-pulsing is not observed as the pump power is more than 2
times higher than lasing threshold of the device.

\[ V = a \left(1 - e^{-t/\tau}\right) + V_0 \]  
(1)

\[ V = a \cdot e^{-t/\tau} + V_0 \]  
(2)

Fig. 3.16(a) Time domain stability of laser signal under different pump power: self-pulsing is
suppressed when pump power is increased (b) The laser signal time response under 200 Hz square
wave modulation applied on the microring heater. (c) The laser signal time response under 2.5 kHz
square wave modulation applied on the gain cavity phase shifter heater.

In order to measure the linewidth of the integrated tunable laser, a delayed self-
heterodyne detection method [63] is used. The setup is shown in Fig. 3.17(a). The laser
signal at 1560.09 nm (after aligning the resonances of two Si3N4 rings as well as the
gain cavity phase shifter) is split into two by a 3dB coupler. One signal goes through
polarization controller 1 (PC 1), and the other signal goes through a delay line. Here,
the delay line is constructed in a circulating loop with a 80/20 splitter. An acousto-optic modulator (AOM) provides a frequency shift of 44 MHz. Since our Er integrated laser has narrow linewidth, a fiber delay of 10 km is used. As the circulation number N increases, the total delay length increases. This circulating structure ensures that there are higher order harmonics of the 44 MHz beatnote which are incoherent with the signal propagating through PC1 after a sufficient number of roundtrips through the circulating arm. As the circulating number N increases, the signal-to-noise-ratio (SNR) in the loop decreases. Hence, an erbium-doped fiber amplifier (EDFA) is used to compensate the loss of the circulating loop and maintain the SNR. A tunable filter (3dB bandwidth of 1 nm) is tuned to the signal wavelength to suppress the amplified spontaneous emission of the EDFA. Beat signals are detected by an electrical signal analyzer (ESA). A stable and narrow linewidth of 340 kHz is observed with no coherence artifacts after an effective delay length of 400 km (400 km/10 km=40th harmonic) for the tunable laser device with a 4.6 cm round-trip cavity length. The 40th harmonic at f=40x44 MHz=1.76 GHz and its Lorentzian fitting is shown in Fig. 3.17(b). The 340 kHz laser linewidth corresponds to a coherence length of 0.6 km, which is significantly shorter than the total 400 km fiber delay length. This verifies that the delay length used here is long enough to ensure incoherence. This is also be verified by the absence of sidelobes in the ESA spectrum.
3.2.3 Laser frequency stabilization

In order to stabilize the signal frequency of the laser device, the laser signal is locked to one of the frequency comb lines generated by a commercial mode-locked laser (MLL, Menlo systems). The frequency locking set-up is shown in Fig. 3.18(a) below. The signal from the integrated tunable laser (TL) is beaten with the comb signal from the MLL through the balanced-photodetector (BPD). The beat signal is then filtered by a bandpass filter (BPF) with a 3-dB bandwidth of 40 MHz centered at 200 MHz. After division by 16 using a frequency divider, the signal-to-noise-ratio (SNR)-enhanced signal is compared with another RF synthesizer reference by a phase detector. The phase detector output serves as the error signal of a proportional-integral (PI) controller, which can lock the tunable laser frequency to the comb line of the MLL by generating the feedback signal to tune the gain-cavity longitudinal-mode phase shifter heater of the tunable laser. To evaluate the locking performance, the beat note is divided by 32 and then measured by a frequency counter. Both the RF synthesizer and frequency counter are referenced to the same 10 MHz clock, which ensures that the measurement results indicate the locking instability itself. The tunable laser was continuously locked to the MLL over 4900 seconds with a peak-to-peak frequency deviation below 10 Hz, as shown in Fig. 3.18(b). During this measurement time, the frequency instability (Allan deviation [89]) relative to the optical frequency at 1560 nm (Fig. 3.18(c)) is below $10^{-14}$ at 1s and approaching $10^{-16}$ after 1000 s. The frequency instability can be further improved by introducing field-programmable gate array (FPGA)-based feedback with a much narrower bandwidth BPF.
3.2.4 Summary

We have demonstrated the first monolithically integrated erbium-doped tunable laser on a CMOS-compatible silicon photonics platform. Two Si$_3$N$_4$ microring resonators are used to form a Vernier cavity for wide-spectrum wavelength tuning, achieved with metal layers deposited for thermal tuning. Erbium-doped Al$_2$O$_3$ is deposited as a back-end step and used as a gain medium for lasing. The tuning range demonstrated is from 1527 nm to 1573 nm, covering the full C band. Within the 46 nm tuning range, a uniform lasing peak with >40 dB SMSR is achieved. A slope efficiency of 2.2% is reported, with 1.6 mW maximum output power. Fine tuning of the signal is
demonstrated by tuning the gain cavity phase shifter. The laser signal response times are measured to be around 200 µs and 35 µs for coarse and fine tuning, respectively. The laser linewidth is measured to be 340 kHz via a delay self-heterodyne detection method. In addition, the laser signal is stabilized by continuous locking to a MLL over 4900 seconds and the peak-to-peak frequency deviation is below 10 Hz.
Chapter 4. Ultra-narrow-linewidth and Reliable Erbium DFB Lasers Monolithically Integrated on a Silicon Photonics Platform

This chapter presents two designs of the erbium doped CW laser monolithically integrated on a silicon photonics platform. The first section demonstrates an ultra-narrow linewidth laser (5 kHz), showing one of the advantages of the erbium doped laser. The second section demonstrates a reliable integrated laser using curved cavity structure, which compensates for the gain film non-uniformity issue within the deposition chamber.

4.1 Ultra-narrow-linewidth erbium doped DFB lasers

Integration of high quality ultra-narrow-linewidth lasers on a silicon photonics platform is important for several applications, including digital coherent communications, coherent LIDAR, optical metrology, and sensing [90]. Hybrid III-V silicon lasers have been shown to generate several MHz optical linewidth with phase-shifted distributed feedback (DFB) cavities [91]. To obtain a kHz linewidth laser, an external cavity can be constructed by combining the semiconductor gain medium with a Vernier-based tunable filter [92] or a high Q resonance cavity can be used with low passive loss [93]. However, these approaches generally require complex fabrication steps, or careful temperature control. Alternatively, monolithic erbium-doped aluminum oxide (Al$_2$O$_3$:Er$^{3+}$) lasers have been shown to achieve linewidths as low as 1.7 kHz using a DFB cavity [35]. Recently, we have demonstrated a CMOS-compatible design to integrate Al$_2$O$_3$:Er$^{3+}$ lasers in a wafer-scale process with a single backend step [41]. The waveguide consists of a thin (~100 nm) silicon nitride (SiN$_x$) structure buried in a silicon dioxide (SiO$_2$) layer to achieve high confinement factor and mode overlap in the gain film [20, 36, 41, 94].

In this section, we extend the design to work for a thicker silicon nitride by using a multi-segmented waveguide structure [18, 81, 95]. This allows integration into a more
general silicon photonics wafer-scale process where thicker, higher-confinement SiN$_x$ structures might be preferred [4, 19, 96]. In addition, the design exhibits the same high confinement factor (> 85%) and a near perfect intensity overlap (> 98%) for an octave spanning range across near infrared (NIR) wavelengths (950–2000 nm).

We compare the performance of DFB lasers in discrete quarter phase shifted (QPS) cavities and distributed phase shifted (DPS) cavities [35, 97]. By using a QPS-DFB configuration, we obtain single frequency lasing at 1536 nm, 1566 nm, and 1596 nm with on-chip output powers of 0.41 mW, 0.76 mW, and 0.47 mW respectively. This spans a similar emission bandwidth that has been shown previously in distributed Bragg reflector (DBR) lasers [41], covering the C and L band of the erbium gain spectrum. In a DPS cavity, we achieve an order of magnitude improvement in maximum output power (5.43 mW) for a wavelength centered at 1565 nm, corresponding to side mode suppression ratio (SMSR) of > 59.4 dB. Using a recirculating self-heterodyne delayed interferometer (R-SHDI) [7, 98], we also observe a narrower linewidth for DPS-DFB at $\Delta$ν$_{DPS}$ = 5.3 ± 0.3 kHz, as compared to QPS-DFB at $\Delta$ν$_{QPS}$ = 30.4 ± 1.1 kHz. The improvement can be explained by reduction of spatial hole burning in the center of cavity and increased effective gain section [99, 100].

4.1.1 Wavelength-insensitive waveguide design

![Diagram](image)

Fig. 4.1(a) Schematic of wavelength-insensitive laser waveguide design by multi-segmented SiN$_x$ structure. (b) Mode-solver calculation of the intensity distribution for various near infrared wavelengths in the multi-segmented waveguide design.

Fig. 4.1(a) shows a schematic of the wavelength insensitive waveguide design. It consists of a silicon (Si) substrate, five SiN$_x$ segments (thickness $t$ of 200 nm, width $w$...
of 450 nm, and gap $g$ of 400 nm), enclosed by a SiO$_2$ layer (oxide gap $g_{ox}$ of 200 nm), and Al$_2$O$_3$:Er$^{3+}$ gain film (thickness $t_{AlO} = 1100$ nm). The fabrication process has been reported in references [41, 83] with the only difference in the layer thickness or dopant. The distance between the Si to the bottom layer of SiN$_x$ (>2.5μm) is sufficient to ensure the fundamental TE mode is not affected by the substrate. We use the prism coupling method to estimate the Al$_2$O$_3$:Er$^{3+}$ gain film background loss of <0.1 dB/cm and dopant concentration of $1.0 \times 10^{20}$ cm$^{-3}$ by linear fitting of measured total film loss ($\alpha_{tot}$) vs. the film absorption cross-section ($\sigma_a$) around 1550 nm based on the following simplified equation:

$$\alpha_{tot} = \sigma_a N + \alpha_b$$

where \(\sigma_a\) is the absorption cross-section of Al$_2$O$_3$:Er$^{3+}$ film at certain wavelength, N is the doping concentration. \(\alpha_{tot}\) and \(\alpha_b\) are the total and background loss of the film respectively.

We perform analysis of the multi-segmented structure for a broad selection of wavelengths relevant to rare-earth emission in the NIR range; 800 nm, 900 nm, 950 nm and 980 nm (diode pump lasers for Er and Yb), 1050 nm (Yb- and Nd-doped lasers), 1300 nm (Nd-doped lasers), 1550 nm (Er-doped lasers), and 2000 nm (Tm- and Ho-doped lasers). The intensity distributions of the fundamental TE modes at the various wavelengths are calculated by a vector finite-difference 2D Eigen mode solver (in-house Matlab code), as shown in Fig. 4.1(b). By inspection of the modes in Fig. 4.1(b), we observe that the mode distribution at shorter wavelengths tends to concentrate in the silicon nitride layer. Starting from 950 nm, the mode is distributed almost exclusively in the gain layer.
Fig. 4.2(a) Calculated confinement factor in the multi-segmented waveguide for typical NIR diode pump and rare earth laser wavelengths. (b) Calculated intensity overlap between 980-nm mode and NIR diode and rare earth laser modes.

We define the confinement factor ($\gamma$) and overlap factor ($\Gamma$) in the active medium by the following equations:

$$\gamma_{s/p} = \frac{\int I_{s/p} dA}{\int I_{s/p} dA} = \frac{\sum_{ij \text{ gain}} I_{ij}^{(s/p)}}{\sum_{ij} I_{ij}^{(s/p)}}$$

$$\Gamma_{s/p} = \frac{\sqrt{\int I_{p} I_{s} dA \int I_{s}^{2} dA}}{\sqrt{\int I_{p}^{2} dA \int I_{s}^{2} dA}} = \frac{\sum_{ij \text{ gain}} I_{ij}^{(p)} I_{ij}^{(s)}}{\left(\sum_{ij \text{ gain}} I_{ij}^{2(p)}\right)^{1/2} \left(\sum_{ij \text{ gain}} I_{ij}^{2(s)}\right)^{1/2}},$$

where $I$ denotes the intensity of the mode. The indicators $s$ and $p$ denote the signal (laser wavelength) and pump wavelength respectively. The integrals are discretized with indices $i$ and $j$, and calculated by summation over each pixel in the simulation window, where the gain area $A$ refers to Al$_2$O$_3$ layer. The confinement and overlap factors (with 980 nm chosen as a reference pump wavelength) for these wavelengths are shown in Fig. 4.2. We obtain >85% confinement factor for all wavelengths longer than 950 nm and >98% intensity overlap factor with a 980 nm pump mode over an octave of near-infrared wavelength light sources, demonstrating the wavelength insensitivity of the waveguide. The calculation is based on the assumption that the laser is pumped with enough power, so that it has gain over the entire waveguide mode. Therefore, the
confinement factor and mode overlap are good estimations for the upper limit of the performance in the optically pumped waveguide. While here we present a design specifically optimized for 980-nm pumping, the wavelength-insensitive range and lower wavelength cutoff can also be shifted by adjusting the waveguide dimensions. In this way, the intensity overlap can be optimized to accommodate different pumping schemes, allowing the design to be used for a variety of rare earth doped lasers.

4.1.2 Numerical simulation methodology

The numerical simulation methodology is summarized in this section. The thulium doped DFB and DBR laser design in Chapter 5 as well as holmium doped DFB laser design in Chapter 6 use the same simulation methodology. The effective indices and guided modes in waveguides are simulated by vector finite-difference 2D eigenmode solver, with a discretization of 20 nm. The code is written in Matlab (Appendix II), and it solves the following wave equation of the transverse electric field:

$$\nabla^2 \vec{e}_t + \nabla \left( \frac{1}{n^2} \nabla (n^2 \vec{e}_t) \right) + n^2 k^2 \vec{e}_t = \beta^2 \vec{e}_t \tag{1}$$

where $k$ is the wave number, $n$ is the refractive index. After solving the above eigen problem, the square of propagation constant $\beta^2$ can be obtained as eigenvalue, and hence effective index is calculated using $n_{\text{eff}} = \beta \lambda / 2 \pi$. The transverse-electric (TE) field intensity of the fundamental mode at the pump and signal wavelengths is shown in Fig. 4.1(b) in this chapter and Fig. 5.6(c) in later chapter. The expected lasing wavelength (as shown in Fig. 5.8 in later chapter) is then calculated by substituting the $n_{\text{eff}}$ obtained into the following equation:

$$\Lambda = \frac{\lambda}{2 n_{\text{eff}}} \tag{2}$$

where $\Lambda$ is the grating period. The grating strength or coupling coefficient ($\kappa$) is calculated using the following equation [101]:

$$\kappa = \frac{k^2}{2 \pi \beta} (n_{SiN}^2 - n_{SiO}^2) \sin(\pi D) \tau \tag{3}$$
where \( D \) is grating duty cycle, which equals to 0.5, \( \tau \) is the mode overlap within the grating region. The transmission of the grating response (Fig. 5.7) is then calculated by substituting the \( n_{\text{eff}} \) and \( \kappa \) obtained into the following transfer matrix of grating [101]:

\[
T = \begin{bmatrix}
\cosh(j\gamma L) - \frac{\sigma}{\gamma} \sinh(j\gamma L) & -\frac{\kappa^*}{\gamma} \sinh(j\gamma L) \\
\frac{\kappa}{\gamma} \sinh(j\gamma L) & \cosh(j\gamma L) + \frac{\sigma}{\gamma} \sinh(j\gamma L)
\end{bmatrix}
\]

(4)

where \( \sigma = 2n_{\text{eff}}\pi / \lambda - \pi / \Lambda \), \( \Lambda \) is the grating period and \( j^2 = \sigma^2 - \kappa^2 \). For DFB grating response, quarter wave phase shift is introduced in the middle of the simulated section, with \( \kappa \) flipping sign: \( \kappa = -\kappa \).

4.1.3 \( \text{Al}_2\text{O}_3: \text{Er}^{3+} \) QPS and DPS DFB lasers

We apply the five-segment wavelength-insensitive design to realize single-frequency and ultra-narrow-linewidth \( \text{Al}_2\text{O}_3: \text{Er}^{3+} \) lasers. We investigate two different phase shift configurations for 2 cm long DFB cavity. In QPS-DFB, a discrete quarter phase shift is formed at the center of the cavity with a sharp frequency resonance at the Bragg wavelength. The intense electric field concentrated around the phase shifted region may limit the performance of the laser due to spatial hole burning. Alternatively, the phase shift in DPS-DFB cavity is continuously distributed in a wider region, thus improving the uniformity of the field distribution and increasing the length of the effective gain section. We compare the performance of the lasers in the following sections.

The grating unit in the QPS-DFB cavities is formed by placing additional periodic pieces on both sides of the five-segment SiNx structure, as shown in Fig. 4.3(a). These periodic side pieces have width \( w_g \) of 300 nm with the grating strength \( \kappa \) adjusted by varying the gap distance \( d_{wg} \). We fabricated a total of 9 devices with 3 grating period variations (\( \Lambda = 482 \text{ nm}, 492 \text{ nm}, \text{ and } 502 \text{ nm} \)) and 3 grating strength variations (\( d_{wg} / \kappa = 600 \text{ nm} / 0.6 \text{ mm}^{-1}, 350 \text{ nm} / 0.9 \text{ mm}^{-1}, \text{ and } 200 \text{ nm} / 1.2 \text{ mm}^{-1} \)).
Fig. 4.3 (a) Design of Al<sub>2</sub>O<sub>3</sub>:Er<sup>3+</sup> QPS-DFB (not to scale). The cavity structure consists of five continuous SiN<sub>x</sub> segments with grating perturbation provided by two additional periodic side pieces. (b) Optical spectrum of Al<sub>2</sub>O<sub>3</sub>:Er<sup>3+</sup> QPS-DFB lasers at various grating periods. (c) On-chip laser power of Al<sub>2</sub>O<sub>3</sub>:Er<sup>3+</sup> QPS-DFB lasers vs. pump power.

To characterize their performance, we pumped the DFB lasers from both sides using fiber pigtail laser diodes at 978 nm and 976 nm. We obtain the best laser performance from devices with \( d_{wg} = 350 \text{ nm} \) or \( \kappa = 0.9 \text{ mm}^{-1} \) for all three wavelengths. Figure 3(b) shows the spectra of DFB lasers operating at 1536 nm, 1566 nm, and 1596 nm, which covers a similar emission bandwidth that has been shown previously in distributed Bragg reflector (DBR) lasers [41]. The highest on-chip output power of 0.76 mW is achieved at 1566 nm. The laser operating at 1536 nm has the lowest output power, corresponding to > 46.1 dB side mode suppression ratio (SMSR) for all devices. We characterize the slope efficiency and threshold power of the lasers, as shown in Fig. 4.3(c). We obtain slope efficiencies \( \eta = 0.3\% \), 0.6\%, and 0.3\% and threshold powers \( P_{th} = 55 \text{ mW} \), 65 mW, and 105 mW for lasers at wavelengths 1536 nm, 1566 nm, and 1596 nm, respectively.

The thermal stability of our DFB is investigated in [38, 79] showing a temperature-
dependent shift of 0.02 nm/°C, which is more than two times lower than the thermal wavelength shift reported for hybrid lasers [102-105]. Such small wavelength shift is contributed by the low thermo-optic coefficients of the Al₂O₃ film and the SiNₓ waveguide. The laser stability over time is mainly affected by mechanical misalignment of the fiber coupling for pump and lasing signal. A short term solution is to isolate the laser chip by covering up the test setup, so that the coupling fiber will be minimally affected by environmental fluctuations. Meanwhile, a long term solution is to integrate the diode pump onto the system so that fiber coupling is not necessary.

The **DPS-DFB** cavities are formed using an asymmetric design which includes a continuous segment with varying width \( w_n(x) \) on one side of the waveguide and periodic pieces with spacing \( d_κ(x) \) on the other side, where \( x \) is the axis along the cavity, as shown in Fig. 4.4(a). This allows accumulation of phase shift by a gradual sinusoidal change of the effective refractive index \( Δn_{\text{eff}}(x) \) [97] while maintaining a constant grating strength \( κ \) in the phase shifted region with length \( L_{ps} \). We use the coupled mode theory [101] to determine the right combination of \( w_n(x) \) and \( d_κ(x) \) for fixed gap distance \( d_n = 250 \) nm and periodic pieces of width \( w_κ = 300 \) nm. We fabricated two different \( L_{ps} \) (0.2 cm and 0.4 cm) for grating period at 492 nm and \( κ = 0.7 \) mm⁻¹. For the 0.2-cm DPS-DFB, \( w_n(x) \) varies from 168–351 nm and \( d_κ(x) \) varies from 119–162 nm. For the 0.4-cm DPS-DFB, \( w_n(x) \) varies from 168–271 nm and \( d_κ(x) \) varies from 140–162 nm.
Fig. 4.4(a) Design of Al₂O₃:Er³⁺ DPS-DFB laser with five-segment SiNₓ waveguide (not to scale). The cavity structure consists of five continuous SiNₓ segments with grating perturbation provided by two additional side pieces, one with a phase shift region (top) and the other with periodic segments (bottom); (b) Optical spectrum of Al₂O₃:Er³⁺ DPS-DFB lasers at various grating periods; (c) On-chip laser power of Al₂O₃:Er³⁺ DPS-DFB lasers vs. pump power.

Fig. 4.4(b) shows the spectrum of the best DPS-DFB with \( L_{ps} = 0.4 \) cm and emission centered at \( \lambda = 1565 \) nm. A maximum on-chip output power of 5.43 mW is obtained, corresponding to a SMSR > 59.4 dB. Fig. 4.4(c) shows the comparison of power performance of the lasers. The longer \( L_{ps} \) DPS-DFB laser has almost double the output power at maximum pump. The threshold power is > 4 times lower than the QPS design (\( P_{th} = 14 \) mW), with close to 5 times improvement in the slope efficiency (\( \eta = 2.9\% \)). These improvements can be attributed to a more uniform and longer active gain section in DPS-DFB. Meanwhile, compare with QPS structure, DPS structure may have slightly higher loss from (a) the asymmetry of the grating (due to transition from symmetric waveguide to asymmetric design), and (b) the tapered structure of the
waveguide on a longer region that is not observed in traditional QPS. This may deviate the performance of DPS structure from theoretical expectation.

4.1.4 Ultra-narrow-linewidth measurement

For an accurate linewidth measurement in a self-heterodyne interferometer, a fiber delay length larger than the laser coherence length is required ($L_{\text{delay}} > L_{\text{coherence}}$) [106, 107]. From the Schawlow-Townes formula, the fundamental (quantum) linewidth limit of an Al$_2$O$_3$:Er$^{3+}$ DFB laser can reach the sub-kHz level [108]. If we assume $\Delta v = 1$ kHz and the speed of light $c/n = 2 \times 10^8$ m/s, then the minimum $L_{\text{delay}}$ needs to be at least 200 km. Such a long fiber requirement can be alleviated in a recirculating SHDI (R-SHDI) configuration [7, 98], as shown in Fig. 4.5. The setup is similar to a standard SHDI, but one of the branches couples to a multipass cavity that consists of a fiber delay and an acousto optic modulator (AOM) for frequency shifting ($f_{\text{AOM}} = 44$ MHz). Thus, the spectrum at frequency $n \times f_{\text{AOM}}$ corresponds to an auto-correlation of the input light after passing through the equivalent delay of $n \times L_{\text{delay}}$. Lastly, an erbium doped fiber amplifier (EDFA), an optical isolator, and a tunable filter are included to compensate for roundtrip loss.

We measured the linewidth of the Al$_2$O$_3$:Er$^{3+}$ QPS-DFB laser centered at $\lambda = 1566$ nm and DPS-DFB laser centered at $\lambda = 1565$ nm, as shown in Fig. 4.6. For QPS-DFB laser, the spectrum was collected at a center frequency of $f_c = 132$ MHz ($n = 3$), which
corresponds to a total delay length of 105 km ($L_{\text{delay}} = 35$ km). For the DPS-DFB laser, $n = 15, f_c = 660$ MHz, and the effective $L_{\text{delay}} = 525$ km. To differentiate the 1/f frequency noise contribution, the measured spectra are fitted with Voigt functions [60, 109]. The self-heterodyne spectra are plotted around $f_c$ with the QPS-DFB laser presented in red color and the DPS-DFB laser in blue color.

By fitting the QPS-DFB spectrum, we obtain a full width half maximum (FWHM) of the Voigt function of $FWHM_{\text{Voigt}} = 66.1 \pm 2.5$ kHz. The Voigt linewidth is further decomposed into the Gaussian component $FWHM_{\text{Gauss}} = 18.4 \pm 7.9$ kHz and Lorentzian component $FWHM_{\text{Lorentz}} = 60.7 \pm 2.2$ kHz. As the self-heterodyne measurement is an autocorrelation process whose FWHM is 2 times the laser linewidth, the optical linewidth $\Delta\nu$ can be estimated from half the Lorentzian width of the spectrum, thus $\Delta\nu_{\text{QPS}} = \frac{1}{2} \times FWHM_{\text{Lorentz}} = 30.4 \pm 1.1$ kHz. For the DPS-DFB laser, with the same analysis above we obtain $FWHM_{\text{Voigt}} = 23.8 \pm 0.7$ kHz, $FWHM_{\text{Gauss}} = 17.5 \pm 1$ kHz, $FWHM_{\text{Lorentz}} = 10.5 \pm 0.5$ kHz, and thus $\Delta\nu_{\text{DPS}} = 5.3 \pm 0.3$ kHz. The linewidth improvement in the DPS-DFB laser ($\Delta\nu_{\text{QPS}} = 5.73 \times \Delta\nu_{\text{DPS}}$) can be attributed to a higher output power and reduction in the spatial hole burning effect.

To our knowledge, this is one of the first demonstrations of a sub-10-kHz-linewidth monolithically integrated laser in a CMOS-compatible silicon photonics platform [35, 91, 92]. The lowest linewidth for an erbium-doped Al$_2$O$_3$:Er$^{3+}$ DFB waveguide laser was obtained in [35]. The linewidth difference between our laser and the ultra-narrow-linewidth laser reported in ref. [35] might be explained by differences in the waveguide and cavity dimensions, the wavelength and linewidth quality of the pump laser and/or the mechanical and environmental stability of the experiment. By careful optimization each of these properties we expect that further reduction of the linewidth can be obtained.
4.1.5 Summary

We demonstrate narrow linewidth Al$_2$O$_3$:Er$^{3+}$ DFB lasers using a multi-segmented SiNx silicon-compatible waveguide design. The waveguide design has $> 85\%$ confinement factor and $> 98\%$ intensity overlap at wavelengths from 950–2000 nm, showing octave-spanning wavelength-insensitivity in the NIR range and enabling efficient pumping at broadly-spaced pump and signal/laser wavelengths. We apply the design to QPS-DFB and DPS-DFB cavities. In the QPS-DFB configuration, we obtain maximum output powers of 0.41 mW, 0.76 mW, and 0.47 mW at widely spaced wavelengths within both the C and L bands of the erbium gain spectrum (1536 nm, 1566 nm, and 1596 nm). In a DPS cavity, we achieve an order of magnitude improvement in maximum output power (5.43 mW) for a wavelength centered at 1565 nm, corresponding to a side mode suppression ratio (SMSR) of $> 59.4$ dB. Finally, we measure the optical linewidths with an R-SHDI setup to obtain $\Delta \nu_{QPS} = 30.4 \pm 1.1$ kHz and $\Delta \nu_{DPS} = 5.3 \pm 0.3$ kHz. The overall improvement of the DPS-DFB cavity can be attributed to the reduction of spatial hole burning in QPS-DFB cavity and a longer effective gain section. Even narrower linewidth can be achieved by mechanical stabilization of the setup, increasing the pump absorption efficiency, increasing the output power, or enhancing the cavity Q. The Q
can be enhanced by accounting for Al$_2$O$_3$:Er$^{3+}$ film thickness variation across the cavity, reducing the SiN$_x$ loss and optimizing the DFB grating strength.

4.2 Reliable erbium doped DFB lasers using curved cavity structure

High quality, single frequency on-chip light sources are required for many applications in silicon photonics technology [2, 102, 110]. Erbium doped aluminum oxide (Al$_2$O$_3$:Er$^{3+}$) distributed feedback (DFB) lasers [18, 20, 111] offer a competitive alternative to hybrid III-V silicon lasers [112-114] for high power [115], narrow linewidth [111], and thermally stable [116] integrated light sources. A CMOS-compatible waveguide design generally consists of a core silicon nitride (SiN$_x$) guiding layer followed by a backend-deposited active film [19, 117, 118]. Thin Al$_2$O$_3$:Er$^{3+}$ films have been consistently grown by many research groups using a reactive co-sputtering process first described by Wörhoff et al. [119]. In a standard sputtering system, the target is mounted on a rotating platform with radially varying thickness profile from the center. Thus, a conventional straight DFB structure would experience thickness non-uniformity along the cavity.

We investigate the influence of film thickness uniformity on cavity Q and threshold power in Al$_2$O$_3$:Er$^{3+}$ DFB lasers, and experimentally measure the thickness variation of the film across a 5-cm radius platform. We show that in a 2-cm-long Al$_2$O$_3$:Er$^{3+}$ DFB laser even for thickness variations of < 0.5%, the cavity response can be highly distorted with significantly reduced Q. A shorter cavity would reduce the thickness variation across the DFB laser, while it limits the single pass absorption efficiency of the pump power. To improve the absorption rate, a higher doping concentration may be considered at the expense of increase in energy-transfer upconversion (ETU) and ion quenching.

In this section, we propose a compensation scheme based on a curved DFB structure that follows the circular symmetry of the deposition system. Under the same grating parameters, an output power of 1.2 mW is achieved in a curved DFB laser,
demonstrating > 6 times lower threshold power compared to a straight DFB laser. The transmission response of the curved DFB structure shows agreement with the ideal DFB structure of uniform thickness.

4.2.1 Analysis of thickness variation in straight DFB laser

![Image]

Fig. 4.7(a) Measurement (black) of the Al$_2$O$_3$ film thickness fitted with a quadratic function (red) at varying distance from the center of the rotating deposition platform. (b) Diagram of the straight DFB laser placement in a radially symmetric Al$_2$O$_3$ film deposition process. (c) Illustration of thickness variation along the Al$_2$O$_3$:Er$^{3+}$ DFB cavity. (d) Calculation of thickness profile in 2-cm-long straight DFB cavities for various tilt angles at $R = 3$ cm.

We measure the thickness variation of an Al$_2$O$_3$:Er$^{3+}$ film deposited in a reactive sputtering system which used 2” Er and Al sputtering targets in a confocal arrangement. The substrate is mounted on a 5-cm-radius rotating platform. After deposition, thickness measurements are performed by prism coupling at various distances $R$ from...
the center of the platform. Several film depositions in the range of 1000-1500 nm are normalized as shown in Fig. 4.7(a). The data is fitted with a quadratic polynomial function, estimating 12% maximum variation across the platform.

Fig. 4.7(b) illustrates a top view of the rotating platform with a straight DFB structure. Different parts of the DFB structure are located at varying distances \( r \) from the center \( O \), thus inducing thickness variation along the device. Furthermore, a non-zero tilt angle \( \alpha \) can introduce additional skew to the profile. This misalignment can also be interpreted as translational error of \((x_{shift}, y_{shift})\) from position where \( \alpha = 0 \) (point \( A \)). The thickness variation along the DFB cavity is illustrated in Fig. 4.7(c). The cavity with length \( D_{DFB} \) with grating period \( \Lambda \) is deposited with base Al\(_2\)O\(_3\):Er\(^{3+}\) thickness of \( T_0 \). The variation \( \Delta t \) along the cavity is skewed for \( \alpha \neq 0 \). The thickness variation is calculated for various tilt angles, \( D_{DFB} = 2 \) cm, and positioning at \( R = 3 \) cm, as shown in Fig. 4.7(d). The thickness is normalized for \( T_0 \approx 1100 \) nm. We obtain a small non-uniformity of 0.5%, 0.5%, and 0.8% for \( \alpha = 0^\circ, 2.5^\circ, \) and \( 5^\circ \) respectively. Fig. 4.8 below shows the transfer matrix calculation of the DFB transmission response with different thickness variation amplitude. The DFB is segmented into 1000 sections, with the effective index \( n_{eff} \) as a function of the film thickness at different \( d \). The Q factor is determined from the ratio of the laser resonant wavelength \( \lambda = 1590 \) nm with the 3-dB width of the resonance peak. It shows that with 0.8% film thickness non-uniformity (~10 nm), the cavity response is distorted significantly and cavity Q is reduced from \( 2.98 \times 10^6 \) to \( 2.94 \times 10^5 \).
Fig. 4.8 Transfer matrix calculation of the DFB transmission response with different thickness variation amplitude (a) $\Delta t = 0$ nm (b) $\Delta t = 5$ nm (c) $\Delta t = 10$ nm (d) $\Delta t = 15$ nm
4.2.2 Compensation scheme by curved DFB structure

Fig. 4.9(a) Diagram of the curved DFB laser placement in a radially symmetric Al$_2$O$_3$:Er$^{3+}$ film deposition chamber. (b) Calculation of thickness profile in a 2 cm long curved DFB cavity for various tilt angles at $R = R_c = 3$cm.

To compensate for the thickness non-uniformity in the deposition, we propose a curved DFB structure that follows the circular symmetry of the platform, as shown in Fig. 4.9(a). By placing the curved DFB at $R = R_c$, the thickness profile can be maintained uniform throughout the cavity. The calculated thickness profile of a 2cm-long curved DFB structure at various angles shows that the profile is linear with smaller magnitude of variation, as shown in Fig. 4.9(b). The radial distance $r$ as a function of position in the device $d$ is calculated by the following formula:

$$r_{(d)}^2 = (x_{shift} + x'_{(d)} \cos \alpha + y'_{(d)} \sin \alpha)^2 + (y_{shift} - x'_{(d)} \sin \alpha + y'_{(d)} \cos \alpha)^2,$$

where $(x_{shift}, y_{shift})$ denotes the relative position of the DFB curvature center (point $O_c$) to the center of the platform (point $O$), and $(x'_{(d)}, y'_{(d)})$ is the position of a segment in the device (point $C$) relative to point $O_c$. These parameters can be calculated by the following relations:

$$x_{shift} = R - R_c \cos \alpha$$

$$y_{shift} = R_c \sin \alpha$$

$$x'_{(d)} = R_c \cos(d/R_c)$$
\[ y'(d) = R_c \sin\left(\frac{d}{R_c}\right) \]

### 4.2.3 Experimental measurement of curved vs. straight DFB laser

We compare the performance of straight and curved Al\(_2\)O\(_3\):Er\(^{3+}\) DFB lasers fabricated on the same chiplet. The lasers are aligned manually at \( R \approx 3 \) cm in the platform. We use a multi-segmented wavelength-insensitive design that consists of a silicon (Si) substrate, five SiNx segments (thickness of 200 nm, width of 450 nm, and gap of 400 nm), enclosed by a SiO\(_2\) layer (oxide gap of 200 nm), and Al\(_2\)O\(_3\):Er\(^{3+}\) gain film (thickness \( T_0 = 1100 \) nm). A discrete quarter phase shift is formed at the center of each cavity to produce sharp resonances at the Bragg condition. The grating is formed by additional periodic pieces on both sides with \( \Lambda = 502 \) nm (\( \lambda_{\text{laser}} \approx 1590 \) nm). These periodic side pieces have width of 300 and gap distance of 350 nm. We use the prism coupling method to estimate a background loss of <0.1 dB/cm and dopant concentration of \( 1.0 \times 10^{20} \) cm\(^{-3}\).

![Experimental setup used for curved Al\(_2\)O\(_3\):Er\(^{3+}\) DFB laser.](image)

**Fig. 4.10** Experimental setup used for curved Al\(_2\)O\(_3\):Er\(^{3+}\) DFB laser.

**Fig. 4.10** shows the experimental setup used for the laser measurement. For the curved DFB structure, the chip edge is angle-etched to provide normally-incident coupling from a fiber. **Fig. 4.11(a) and (b)** shows the transmission measurements of the unpumped straight and curved DFB lasers, respectively. The straight DFB structure contains similar features to those calculated in the previous section, with many distorted peaks emerging in the blue-shifted wavelengths of the resonance. The resonance peak does not have a clear 3-dB width for Q estimation. The curved DFB structure shows a symmetric response, with measured \( Q = 4.55 \times 10^5 \).
We pump the DFB lasers from both sides using fiber pigtail laser diodes at 978 nm and 976 nm. Fig. 4.11(c) shows > 6 times improvement in the threshold power for the curved DFB ($P_{th} = 16$ mW) compared to the straight DFB ($P_{th} = 105$ mW) laser, with similar slope efficiencies (0.6-0.7%). At total pump power of 188 mW, we obtain maximum output power of 1.2 mW for the curved DFB laser and less than 0.5 mW for the straight DFB laser. Lastly, Fig. 4.11(d) shows the output spectra of both lasers, demonstrating a side mode suppression ratio (SMSR) of 55.7 dB for the curved DFB laser.

Fig. 4.11 Experimental measurement of straight and curved Al$_2$O$_3$:Er$^{3+}$ DFB lasers. (a) Transmission measurement of straight DFB cavity. (b) Transmission measurement of curved DFB cavity. (c) Comparison of output powers of straight and curved DFB lasers at different pump powers. (d) Optical spectra of straight and curved DFB lasers.
4.2.4 Summary

To sum up, in this section we investigate the influence of Al$_2$O$_3$:Er$^{3+}$ film thickness uniformity on cavity Q and threshold power in Al$_2$O$_3$:Er$^3$ DFB lasers. For thickness variations of $<0.5\%$ in a 2-cm-long straight DFB cavity, the transmission response can be highly distorted with significantly reduced Q. We propose a compensation scheme based on a curved DFB structure that follows the circular symmetry of the Al$_2$O$_3$:Er$^{3+}$ thin film deposition system. Under the same deposition conditions and grating parameters, the curved design outperformed the conventional straight DFB structure. We achieve a slope efficiency of 0.7 $\%$, threshold power of 16 mW, and maximum output power of 1.2 mW for the curved DFB laser. In the straight DFB laser, we obtain slope efficiency of 0.6 $\%$, threshold power of 105 mW, and maximum output power of 0.5 mW, demonstrating $>6$ times threshold power improvement.
Chapter 5. Thulium Lasers Monolithically Integrated on a Silicon Photonics Platform

This chapter presents two different designs of thulium doped integrated laser. The first section discusses a low lasing threshold, ultra-compact and high efficiency thulium doped laser using the ring cavity structure. It demonstrates high efficiency emission capability of thulium doped gain media on our CMOS-compatible silicon photonics platform. The second section discusses high power distributed feedback (DFB) laser and distributed Bragg reflector (DBR) laser monolithically integrated on a silicon photonics platform. The gain is provided by Al₂O₃:Tm³⁺ thin film, and the feedback is provided by silicon nitride Bragg grating. It further proves a high power emission capability at 1.9 µm of our thulium doped Al₂O₃ platform, for the pulse generator part under the DODOs project as mentioned in the previous project scope section.

5.1 Ultra-compact and low-threshold thulium microcavity laser

Laser sources in the 2 µm wavelength region have many applications such as LIDAR, spectroscopy, optical waveform generation and synthesis, material processing, communication, and trace-gas detection systems. The high water absorption at 2 µm also makes such lasers good candidates for medical applications [120]. Furthermore, 2 µm wavelength lasers in pulsed mode could be used as pumps for nonlinear processes in silicon such as mid-IR optical parametric amplification (OPA) [121]. Thus far, ~2 µm thulium lasers have been developed on a variety of photonic platforms, including bulk crystals [122-124], glass fibers [125-128], planar and channel waveguides [129-135], and whispering-gallery microresonators [136-138].

Silicon is currently under intensive development as a platform for low cost, energy efficient, and high speed integrated photonic microsystems, especially for the traditional communications wavelength bands around 1.3 and 1.5 µm. Recently, however, intensive research has been applied towards extending the operational range
of silicon photonic systems beyond 1.5 \( \mu \text{m} \) for communications, sensing, and advanced metrology applications. In particular, there is a focus on an emerging 2-\( \mu \text{m} \) silicon photonics window, motivated in part by the development of low-loss photonic crystal fibers, extended-range silicon detectors, and thulium fiber amplifiers [139-141].

Since silicon itself is a poor light emitter, compact, efficient and monolithic silicon-based light sources operating near 2 \( \mu \text{m} \) are desirable. However, despite their high performance in other platforms, and the realization of 1.5-\( \mu \text{m} \) erbium- and other rare-earth-doped glass lasers on silicon [15, 41, 142], silicon-integrated thulium lasers are to-date minimally explored. To extend the applicability of silicon photonics microsystems to the 2 \( \mu \text{m} \) wavelength region, complementary metal-oxide semiconductor (CMOS) compatible integrated laser sources around 2 \( \mu \text{m} \) are critical. These lasers will enable highly compact devices that can perform the task of current complex bulky laboratory setups. While thulium microlasers have been demonstrated on silicon chips [143, 144], their design required an off-chip fiber for pump coupling and laser emission. To implement thulium microlasers within silicon photonic microsystems, they must be co-integrated with on-chip waveguides and fabricated using silicon-compatible methods.

In this section, we report on thulium-doped microcavity lasers co-integrated with silicon nitride bus waveguides on silicon. The 200-\( \mu \text{m} \)-diameter thulium microlasers are enabled by a novel high quality factor (Q-factor) microcavity design, which includes two silicon nitride layers and a silicon dioxide trench filled with thulium-doped aluminum oxide (Al\(_2\)O\(_3\):Tm\(^{3+}\)). We show sub-milliwatt threshold and high efficiency lasing around 1.8–1.9 \( \mu \text{m} \) under resonant pumping at 1.6 \( \mu \text{m} \). The entire fabrication process is silicon-compatible and allows for co-integration of such lasers with other silicon-based photonic devices and microsystems.

### 5.1.1 Microcavity fabrication and design

We fabricated the thulium microcavity lasers using a 300-mm CMOS foundry with a 65-nm technology node. A similar fabrication process with erbium and ytterbium applied as dopants is explained in detail in ref. [15]. First, we deposited a 6-\( \mu \text{m} \)-thick plasma-enhanced...
chemical vapor deposition (PECVD) SiO$_2$ bottom cladding layer on a 300-mm silicon wafer, followed by deposition and patterning of two 200-nm-thick PECVD Si$_3$N$_4$ layers with a 100-nm-thick SiO$_2$ layer in between. We patterned both Si$_3$N$_4$ layers using 193-nm immersion lithography and reactive ion etching (RIE), yielding Si$_3$N$_4$ waveguide widths of 0.3 and 0.9 µm (designed for phase-matched 780- and 1610-nm pumping, respectively) and microcavity-waveguide gaps ranging from 0.2 to 1.3 µm (in 0.1 µm steps). We deposited a 4-µm-thick SiO$_2$ layer over the top, then patterned and etched 4-µm-deep microcavity trenches (outer diameter = 200 µm) through RIE process using the upper Si$_3$N$_4$ layer as an etch stop. After removal of the Si$_3$N$_4$ top layer (except for the top part of the waveguide and residual pieces at the edge of the microcavity), we deposited an additional 100-nm-thick SiO$_2$ layer into the trenches. We then etched deep trenches at the edge of the chips for dicing and fiber end-coupling, transferred the wafers from the silicon foundry and diced the wafers into individual dies. We loaded several dies into the sputtering chamber and deposited a 1.5-µm-thick Al$_2$O$_3$:Tm$^{3+}$ film on top. A thinner layer is deposited on the cavity sidewalls due to the angle of the sputtering guns. For this work we selected a sputtering power of 15 W and thulium concentration of 2.5 × 10$^{20}$ cm$^{-3}$ – high enough to achieve greater gain than cavity losses, but low enough to maintain low threshold lasing (determined based on a Q-factor of up to 5.7 × 10$^5$ obtained at 1550 nm in [15]). The aluminum oxide micro-trench cavity fabrication process is shown in Fig. 5.1, presenting the silicon photonics platform as well.

Fig. 5.2(a) shows a schematic of the microcavity laser. The cavity consists of a 15-µm-wide and 5-µm-deep circular trench etched into a SiO$_2$ cladding and filled with a 1.5-µm-thick Al$_2$O$_3$:Tm$^{3+}$ film. The cavity design reported here is also similar to that in ref. [15], but the feature dimensions are different and the design has been simplified by removing the silicon nitride rings below the cavity. The bus waveguide is adjacent to the microcavity and consists of two 200-nm-thick Si$_3$N$_4$ layers separated by a vertical 100-nm SiO$_2$ gap. Because the upper Si$_3$N$_4$ layer also acts as an etch stop during the trench etch [15], small (~300-nm-wide) pieces of Si$_3$N$_4$ remain at the edge of the trench. Based on finite element mode solver calculations, we selected the outer diameter of the microcavity to be 200 µm to minimize bending loss and support high quality factor lasing modes around 1.8–1.9 µm. We also selected a nominal Si$_3$N$_4$
bus waveguide width of 915 nm for phase-matched coupling of pump light at wavelengths around 1.6 µm. We fabricated devices with waveguide-microcavity gaps of 0.2–1.3 µm to investigate a range of coupling strengths. A cross-section drawing of the laser structure (taken at location indicated by the green dashed line) is shown in the inset of Fig. 5.2(a). The deep trench has an angle of ~85°, while the Al₂O₃:Tm³⁺ film in the middle of the trench is thicker than that along the trench edge due to the angular dependence of the reactive co-sputtering deposition process [15, 145]. The simulated mode profiles for 1.6 and 1.8 µm wavelengths are also displayed in the inset of Fig. 5.2(a), showing large overlap with the Al₂O₃:Tm³⁺ layer and pump/laser mode overlap, important for achieving optical gain and lasing [15]. To obtain an accurate profile of the resulting microcavity structure, we first deposited a layer of platinum (Pt) on the microcavity sample and then cut it along the black dotted line indicated in Fig. 5.2(a) using a focused ion beam (FIB). The layer of Pt is deposited on the chip before FIB cutting of the cross section as a protective layer and is not a part of the cavity design. The resulting cross-sectional scanning-electron-micrograph (SEM) image of the microcavity is shown in Fig. 5.2(b). The trench has a depth of around 5.2 µm and a sidewall angle of ~85°. The image was taken with a sample tilt of 52° to the horizontal plane. Taking the tilt angle into account, we calculated the ratio between the Al₂O₃ film thickness on the sidewall and the total deposited film thickness (measured away from the edge of the trench, defined as T in Fig. 5.2(b)) to be 0.44. A magnified view of the area enclosed in the red box in Fig. 5.2(b) is shown in Fig. 5.2(c). Fig. 5.2(d) displays a top-view optical microscope image of a fabricated device.
Fig. 5.1 Aluminum oxide micro-trench cavity fabrication process: (i) PECVD deposition and (ii) patterning of a 200-nm-thick Si₃N₄ film; (iii) deposition and planarization of a PECVD SiO₂ layer to a height of 100 nm above the first Si₃N₄ layer and deposition of a second 200-nm-thick Si₃N₄ film; (iv) patterning of the second Si₃N₄ film; (v) deposition and planarization of a ~5-µm-thick SiO₂ top cladding; (vi) definition of the micro-trench into the SiO₂ cladding using RIE and the second Si₃N₄ layer as an etch stop followed by deposition of a 100-nm-thick SiO₂ layer; and (vii) deposition of a ~1-µm thick Al₂O₃ layer by reactive sputtering. Steps i–vi are completed in a silicon foundry, while step vii is carried out as a post-processing step.
Fig. 5.2(a) Schematic of on-chip thulium microcavity laser. Inset: cross-section of the laser structure and resonant mode profiles for 1.6 μm (pump) and 1.8 μm (signal) wavelengths in the cavity. (b) Cross-sectional SEM image taken along the dotted line
in (a). The Pt coating is used as a protective layer during the FIB cutting of the chip and is not a part of the cavity design. (c) Magnified image of the cross-section (marked by the red rectangle in (b)) showing the trench angle, silicon nitride waveguide and gap. (d) Top-view optical microscope image of a fabricated device, showing the integrated thulium-doped aluminum oxide microresonator and Si₃N₄ bus waveguide (red dashed line).

5.1.2 Laser characterization

We characterized the microcavity lasers using the experimental setup shown in Fig. 5.3(a). We coupled pump light either from a laser diode (780 nm) or a narrow linewidth (100 kHz), tunable (1500–1625 nm) laser to a polarization controller to adjust the input light to transverse-magnetic (TM) polarization, and onto the chip via a tapered fiber. Due to the degeneracy of the clockwise and counter-clockwise modes inside the cavity, lasing occurs in both directions. Therefore, we coupled the laser output in the bus waveguide off chip from both sides using tapered fibers, followed by WDMs to separate the input/residual pump light, and then collected it at optical spectrum analyzers (OSAs) to measure the optical power and emission spectrum. We measured the transmitted pump power using an optical power meter. The energy level and common pumping scheme of thulium ion is shown in Fig. 5.3(b) below. For pumping of singly-doped thulium, the absorption bands of interest lie at wavelengths of 0.78 μm (³H₄ level) and 1.61 μm (³F₄ level). Pumping of the ³H₄ level can be addressed by 0.78 μm laser diodes, with power up to a few hundreds of mW. Pumped at this wavelength, thulium ion has cross relaxation process, as marked in green dotted line in Fig. 5.3(b). During this process, the energy released from decay process (³H₄ → ³F₄) is transferred to excite a nearby ion from ³H₆ to ³F₄, and hence increase the efficiency of the emission.
Fig. 5.3(a) Experimental setup used for thulium-doped microcavity laser measurements. 780 or 1610 nm tunable laser pump light is coupled into the chip through a polarization controller and a fiber wavelength division multiplexer (WDM). The laser output is measured at the optical spectrum analyzers (OSAs) on both sides of the chip; (b) 3-level thulium ion energy diagram showing pump and emission transitions.

We first characterized the lasers using a 780-nm diode pump. Demonstration of lasing via 780-nm pumping is of interest because of the availability of low-cost and efficient near infrared (NIR) diode pumps and the associated “two for one” Tm$^{3+}$ ion excitation via cross-relaxation between neighboring ions, as shown in Fig. 5.3(b). Although the relatively broad-band diode pump light (shown in Fig. 5.4(a)) is only minimally absorbed at the cavity resonances, we observe lasing around 1860-1890 nm
for gaps of 0.2 and 0.3 \(\mu\text{m}\). We did not observe lasing at larger gaps, which we attribute to low pump coupling into the cavity. The output spectrum of a device with gap 0.2 \(\mu\text{m}\) under 780-nm pumping is displayed in Fig. 5.4(b).

We next measured the lasers using a 1.6-\(\mu\text{m}\) tunable laser (100 kHz linewidth), enabling resonant pumping and accurate determination of the pump light absorption and laser performance. The transmission spectrum of a device with a gap of 0.9 \(\mu\text{m}\) measured from 1593 nm to 1615 nm is shown in Fig. 5.5(a). Three different radial modes are marked with arrows on Fig. 5.5(a) around a wavelength of 1608 nm (each with a free-spectral-range of \(\approx 2\) nm). Modes with the same azimuthal order as the one marked with red circle on Fig. 5.5(a) were found to provide lasing behavior, as predicted by calculations taking into account the quality factor, confinement within the gain medium and overlap of the pump and lasing modes.

In Fig. 5.5(b), we show the resonantly absorbed 1608-nm pump power vs. microcavity-waveguide gap size. With TM input, we observed optimum pump coupling of 95\% near a gap width of 0.5 \(\mu\text{m}\). However, lasing did not occur for gap sizes < 0.7 \(\mu\text{m}\). For gap sizes below 0.7 \(\mu\text{m}\), the total cavity Q-factor for lasing wavelengths \(\geq 1.8\) \(\mu\text{m}\) becomes too low, leading to a roundtrip net loss or a lasing threshold that is beyond the maximum output power of the tunable laser utilized in the experiment. We observed lasing behavior at waveguide-microcavity gap sizes ranging from 0.7 to 1.3 \(\mu\text{m}\).
Fig. 5.5(a) TM-polarized transmission spectrum for a device with gap 0.9 µm over the wavelength range 1593 to 1615 nm, showing 3 clear resonant modes of different radial orders (marked by red arrows) within one free-spectral-range. The mode that leads to low threshold lasing is marked with a red circle. (b) Coupled pump power for the pump mode circled in (a) in Tm-doped microcavities with bus waveguide width of 0.9 µm and microcavity-waveguide gap sizes ranging from 0.2 µm to 1.3 µm. Maximum coupling occurs at gaps near 0.5 µm when the internal and external Q-factors of the resonator are matched.

We observed the highest laser output power when resonantly pumping at a wavelength around 1608 nm, near the peak of the thulium ion $^3\text{H}_6 \rightarrow ^3\text{F}_4$ absorption cross-section. Fig. 5.6(a) shows the total (double-sided) on-chip laser power as a function of on-chip pump power for different pump wavelengths and a gap of 0.9 µm. While it shows similar lasing threshold for pump wavelengths from 1594 nm to 1614 nm, pumping around 1608 nm shows the highest slope efficiency. Fig. 5.6(b) shows the lasing thresholds and double-sided slope efficiencies under 1608-nm pumping with respect to microcavity-waveguide gap sizes. A double-sided slope efficiency as high as 24% and threshold as low as 773 µW were observed for gap sizes of 0.9 and 1.0 µm, respectively, with respect to pump power coupled into the Si$_3$N$_4$ bus waveguide. Accounting for the absorbed pump power for different microcavity-waveguide gap sizes shown in Fig. 5.6(c), we determine a maximum double-sided slope efficiency of 48%
with respect to the cavity-coupled pump power for the laser device with 1.1 μm microcavity-waveguide gap size. We observed a minimum threshold of 226 μW vs. absorbed pump power at the largest gap size of 1.3 μm, where the total cavity Q-factor is the highest.

Fig. 5.6(a) On-chip laser power as a function of on-chip pump power for different pump wavelengths for a device with 0.9 μm gap size, showing highest-efficiency lasing and output power > 200 μW when resonantly pumped at 1608 nm. (b) Lasing thresholds and slope efficiencies with respect to on-chip pump power for different microcavity-waveguide gap sizes. (c) Lasing thresholds and slope efficiencies with respect to absorbed power for different microcavity-waveguide gap sizes.
Fig. 5.7 shows laser output spectra measured on one side of the chip for microcavity-waveguide gap sizes ranging from 0.7 \( \mu \text{m} \) to 1.3 \( \mu \text{m} \). We observe multi-mode lasing and laser modes spanning from 1.8 \( \mu \text{m} \) to 1.9 \( \mu \text{m} \). The devices tend to lase at longer wavelengths for larger gap sizes. This trend can be explained by the gap size and wavelength dependence of the loaded cavity Q-factor; the shape of the thulium emission spectrum with its peak near 1.8 \( \mu \text{m} \); and the blue-shifted Tm\(^{3+}\) absorption spectrum with respect to the emission spectrum. For smaller gap sizes (and longer wavelengths), the cavity modes have a greater coupling strength and lower Q-factor (higher roundtrip loss), making the microcavity more likely to lase on higher gain modes near emission peak at 1.8 \( \mu \text{m} \). For larger gap sizes, the Q-factor of all cavity modes increases (roundtrip loss decreases), thus the laser output shifts to longer wavelengths where the Tm\(^{3+}\) absorption is lower and population inversion is more easily achieved. This trend indicates that by increasing the gap width beyond 1.3 \( \mu \text{m} \), longer wavelength lasing could possibly be achieved. Further, by reducing the bus waveguide width for phase-matched pumping at shorter wavelengths, we can pump the microcavity lasers with low-cost, efficient 780-nm lasers. This can potentially lead to an even higher lasing efficiency due to “two for one” excitation via Tm\(^{3+}\)-Tm\(^{3+}\) ion cross-relaxation [122]. Finally, by adding grating features [146] and asymmetry to the cavity, single-mode or directional lasing [147] can also be achieved.
Fig. 5.7 Laser emission spectra under 1608-nm pumping and at microcavity-waveguide gaps of (a) 0.7 μm, (b) 0.9 μm, (c) 1.1 μm, and (d) 1.3 μm, showing a shift of lasing signals to longer wavelengths with the increase of microcavity-waveguide gap size.

### 5.1.3 Single mode lasing in microring laser design

Although the most of the thulium doped microring laser was measured to have multimode lasing, single mode lasing was also observed on some chips at the edge of the wafer. The locations of single mode and multimode laser are shown in Fig. 5.8 below. The chip circled with the blue dotted line on the Softtail 6 wafer is selected for further
characterization. As the gap between the Si$_3$N$_4$ waveguide and the microring is more than 500 nm and less than 1000 nm, the microring has single mode lasing. The single mode lasing spectrum is shown in Fig. 5.9. The device with a gap of 900 nm is selected for the lasing power characterization. The measurement result is shown in Fig. 5.10 below. The power is collected from both output sides of the microring laser device. The power characterization setup is the same as shown in Fig. 5.3(a). Fig. 5.10 shows a 10% slope efficiency, with a lasing threshold of 0.6 mW. This is lower than the multimode case reported earlier. As the gap between Si$_3$N$_4$ waveguide and the microring is increased beyond 1000 nm up to 1300 nm, the multimode lasing is observed, as shown in the Fig. 5.11. As the waveguide-microcavity gap increases, the lasing wavelength shifts to longer wavelength due to the higher coupling at longer wavelength as the gap increases. In addition, the laser does not lase under the condition that the gap is below 600 nm, due to the low coupling efficiency of the optical mode from Si$_3$N$_4$ waveguide to Al$_2$O$_3$ microring. The reason for single mode lasing within the microring cavity can be attributed by the relatively higher coupling of a single mode. Such single mode coupling may be due to the layer offset at the edge of the wafer. Such layer offset introduces strong wavelength dependent coupling.
Fig. 5.8 Location of single mode lasing chip and multimode lasing chip on the wafer. The chip circled with blue dotted line is selected for further characterization.

Fig. 5.9 Single mode lasing spectrum for different Si₃N₄-to-microring from 600 nm to 900 nm. The lasing wavelength shifts to a longer range as the gap increases.

Fig. 5.10 Single mode laser device on-chip output power with respect to on-chip pump power, showing 10% slope efficiency and 0.6 mW lasing threshold
Fig. 5.11 Multimode lasing spectrum as the waveguide-microcavity gap increases beyond 900 nm, showing the shift to longer wavelength as the gap increases.
5.1.4 Summary

To sum up, we have demonstrated low threshold and high efficiency thulium-doped microcavity lasers which are monolithically integrated on a silicon photonic chip. The lasers have thresholds as low as 773 (226) µW and slope efficiencies of up to 24% (48%) vs. on-chip (absorbed) pump power. By changing the waveguide-microcavity gap and resonantly pumping at 1608 nm, we show multimode lasing in the range 1.8–1.9 µm. In future, optimizing the Tm$^{3+}$ concentration, coupling strength, and cavity design can lead to even greater efficiencies, emission over a wider wavelength range across thulium’s broad gain spectrum (~1.7–2.2 µm), single-mode operation and directionality. These results demonstrate integrated thulium lasers to be of interest as highly efficient monolithic light sources for emerging silicon-based photonic microsystems.

5.2 High-power thulium DFB and DBR Lasers

The state-of-the-art for high-power lasers fabricated using Al$_2$O$_3$ as gain medium was demonstrated to be 75 mW continuous-wave (CW) output power in an erbium-doped waveguide laser operating around 1.55 µm [148]. Among rare-earth elements, thulium is particularly attractive for integrated lasers on silicon since its emission spectrum is around 2 µm. Integrated thulium-doped channel waveguide lasers on tungstate were reported with high power and slope efficiencies [135, 149]. However, so far work on thulium-doped high-power lasers on a CMOS-compatible platform has been absent.

Prior to this work, our group have reported a thulium-doped microcavity laser with sub-milliwatt output power and multi-mode operation [19, 83], as presented in earlier section of the same chapter. However, high output power and single-mode operation are desired for many applications. In this section, we demonstrate high-power thulium-doped waveguide lasers that were fabricated on silicon chips in a 300-mm CMOS foundry. An Al$_2$O$_3$:Tm$^{3+}$ thin film deposited as a gain medium on top of a buried Si$_3$N$_4$ strip in SiO$_2$ acts as a rib waveguide on a silicon substrate. The narrow reflection bandwidths of distributed feedback (DFB) and distributed Bragg reflector (DBR) structures enable single-mode output. The maximum on-chip lasing power achieved for
the DFB and DBR devices were 267 mW and 387 mW, with slope efficiencies of 14% and 23%, respectively. Additionally, the lasers with same DFB and DBR structure and Er\(^{3+}/\text{Tm}^{3+}\) co-doped film as gain medium are demonstrated. Lasing with >50 dB SMSR is obtained across the gain spectrum of thulium, pumped at erbium absorption peak (1480 nm). 2.2% slope efficiency and 100 mW lasing threshold with respect to absorbed pump power are reported.

### 5.2.1 DFB and DBR laser design and fabrication

The waveguide cross-section of the DFB laser is shown in Fig. 5.12(a). The width and separation of the Si\(_3\)N\(_4\) bars are optimized to be 300 nm and 350 nm respectively to provide high mode confinements for both pump and signal modes within the Al\(_2\)O\(_3\):\text{Tm}^{3+} \) film. The confinement factors within the thulium-doped gain region for pump and signal are calculated to be 90% and 85% respectively using a finite-difference 2D mode solver. The oxide gap between the Si\(_3\)N\(_4\) layer and the Al\(_2\)O\(_3\) layer is 200 nm. The refractive indices of the materials used in our laser at both pump and signal wavelengths are listed in Fig. 5.12(b). The transverse-electric (TE) field intensity of the fundamental mode is shown in Fig. 5.12(c). For the DBR laser, the gain waveguide cross section has seven Si\(_3\)N\(_4\) bars instead of five. Gratings are added on both sides of the gain waveguide. We designed DFB and DBR cavities for different laser wavelengths by varying the grating periods.

Perspective views of the DFB and DBR lasers are illustrated in Fig. 5.12(d) and (e) respectively. For the DFB laser, the lateral gap between the grating and gain waveguide is designed to be 450 nm, and the grating width is chosen to be 260 nm in order to provide enough feedback at the designed laser wavelength. The coupling coefficient (\(\kappa\)) is calculated to be \(1.0\times10^3 \text{ m}^{-1}\). For the DBR laser, the grating width and gap follow the pattern of seven Si\(_3\)N\(_4\) strips of gain waveguide between two DBR mirrors, with coupling coefficient (\(\kappa\)) of \(1.3\times10^3 \text{ m}^{-1}\). The cavity lengths for both lasers are 2 cm, limited by the maximum length of the chip. For a laser cavity length shorter than 2 cm, with the same pump power, the lasing power decreases. The coupling coefficient and cavity length product (\(\kappa \cdot L\)) for DFB and DBR are 20 and 26 respectively. The grating
responses are calculated using transfer matrix method. Fig. 5.13 below show the typical response for DFB cavity and DBR mirror, with resonance wavelength of 1900 nm. For DFB response calculation, a quarter-wave phase shift is introduced in the middle of simulated section, with $\kappa$ reversing sign: $\kappa = -\kappa$. The grating simulation code is attached in Appendix III at the end of the thesis.

By characterizing the cavity response of the DBR laser, the reflectivity of the grating on each side is estimated to be 70%. Such grating reflectivity enables the laser to achieve a few hundred mW of output power, while still maintain relatively high Q of the DBR cavity. The effective refractive index ($n_{\text{eff}}$) of the waveguide is calculated using a finite-difference 2D mode solver, considering the grating as perturbations on both sides of the segmented Si$_3$N$_4$-rib to provide feedback. The $n_{\text{eff}}$ is calculated to be 1.565. The grating period ($\Lambda$) can be obtained using the following equation:

$$\Lambda = \frac{\lambda}{2n_{\text{eff}}}$$  \hspace{1cm} (1)

where $\lambda$ is the designed laser wavelength. Fig. 5.14 below shows the selected grating period design that we have put down in our mask with respect to different lasing wavelengths.
Fig. 5.12 Integrated thulium DFB and DBR laser designs. (a) Cross-section of the laser gain waveguide including five strips of Si$_3$N$_4$. (b) Refractive indices of the waveguide materials at both pump and signal wavelengths. (c) Fundamental TE field intensity for the pump (1600 nm) and laser output (1900 nm).
nm) wavelengths in the DFB waveguide. 3D illustrations of (d) the DFB laser and (e) the DBR laser, showing the different material layers and cavity features (not to scale).

Fig. 5.13 The selected grating period design that we have put down in our mask with respect to different lasing wavelengths.
The selected grating period design that we have put down in our mask with respect to different lasing wavelengths.

The lasers were fabricated in a state-of-the-art CMOS foundry on a 300-mm silicon wafer. The fabrication process is illustrated in Fig. 5.15(a). The Si$_3$N$_4$ layer is deposited on top of a SiO$_2$ layer, both via plasma-enhanced chemical-vapor deposition (PECVD), followed by a surface polishing process to reduce optical scattering loss. Then the Si$_3$N$_4$ layer is patterned using 193-nm immersion lithography and reactive ion etching, as shown in step II. Next, in step III, we deposit a SiO$_2$ layer and planarize the top surface via chemical-mechanical polishing (CMP). The thickness of the SiO$_2$ layer on the Si$_3$N$_4$ layer is 200 nm. After that, the Al$_2$O$_3$:Tm$^{3+}$ film is deposited at a thickness of 1100 nm via reactive co-sputtering as shown in step IV. The substrate temperature is measured to be 350 °C using a thermocouple directly in contact with chip. The background loss of the Al$_2$O$_3$:Tm$^{3+}$ film is measured to be <0.1 dB/cm. Fabrication runs with different doping levels revealed an optimum Tm$^{3+}$ doping concentration of $3.0 \times 10^{20}$ cm$^{-3}$. At the same pump power, but lower doping concentration, the lasing power of the device decreases due to lower gain; while for higher doping concentration, the lasing power of the device decreases due to doped-ion clustering or quenching [84, 85, 148]. In order to visualize the Si$_3$N$_4$ pattern, after step III and before step IV, 140s hydrogen fluoride (HF) etching is used to remove the SiO$_2$ top cladding. A scanning electron microscope (SEM) image of the gain waveguide and side gratings is shown in Fig. 5.15(b).
Fig. 5.15(a) Laser fabrication steps: (I) deposition of Si$_3$N$_4$ layer via PECVD; (II) patterning of Si$_3$N$_4$ layer yielding 5-segment (DFB) or seven-segment (DBR) waveguides in the center for mode confinement and additional periodic segments at each side for distributed feedback; (III) deposition of SiO$_2$ followed by top surface planarization; (IV) deposition of the thulium-doped Al$_2$O$_3$ gain medium by reactive co-sputtering. (b) SEM image of the Si$_3$N$_4$ pattern after HF etching of the SiO$_2$ top cladding from Step III.

5.2.2 Laser characterization
As mentioned in earlier section and Fig. 5.3(b), the thulium ion can be pumped at 0.78 μm (3H4 level) by laser diodes with power up to a few hundreds of mW. However, the laser output power is limited by the pump power level. An alternative pumping scheme is to pump thulium ion directly to 3F4 level through 1.6 μm pump source. This pumping scheme is able to provide higher thulium laser power since high pump power (up to ~10 W) can be achieved by using high power erbium doped fiber amplifier (EDFA). The spontaneous emission of thulium ion under low pump power is shown in Fig. 5.16 below. It shows that the emission range is from 1680 nm up to 2020 nm, with 3-dB bandwidth of 340 nm. Lasing within this emission range will be demonstrated in later part of this section.

![Graph showing broadband spontaneous emission of Al2O3:Tm3+ film covering from 1680 nm to 2020 nm, with 3-dB bandwidth of 340 nm.](image)

**Fig. 5.16** Broadband spontaneous emission of Al2O3:Tm3+ film covering from 1680 nm to 2020 nm, with 3-dB bandwidth of 340 nm.

The measurement setup for characterizing the lasers is illustrated in Fig. 5.17(a). A laser source at 1612 nm together with an L-band EDFA were used for optical pumping. A polarization controller was used to ensure that the pump light was coupled into the fundamental TE mode of the gain waveguide. A cleaved single-mode SMF-28 fiber was used to butt-couple the pump light onto the chip, and another cleaved single-mode SM2000 fiber was used to butt-couple the output signal of the laser from the chip. The fiber-to-chip coupling losses were measured to be 7.1 dB for SMF-28 at the pump wavelength, and 7.9 dB for SM-2000 at the laser output wavelength. The output signal
was coupled into an optical spectrum analyzer (Yokogawa AQ6375) to capture the spectrum. The grating period design variations are 581 nm, 587 nm, 594 nm, 601 nm, 608 nm and 625 nm. They were calculated using equation (1), with corresponding wavelengths at 1820 nm, 1840 nm, 1860 nm, 1880 nm, 1900 nm and 1950 nm respectively. The measured optical spectra of the corresponding DFB laser designs are shown in Fig. 5.17(b). Within the broad gain bandwidth of the Al₂O₃:Tm³⁺, we are able to precisely control the laser wavelength by choosing the proper grating period.

From the DFB and DBR laser grating period design variations, we selected the devices that operate near the peak of the thulium emission spectrum for the lasing slope efficiency measurements. The slope efficiency curves for DFB and DBR lasers are shown in Fig. 5.18(a) and (b) respectively. The maximum on-chip laser output power of the DFB and DBR lasers were measured to be 267 mW and 387 mW, respectively. The powers were measured from a single output end of the lasers, and the fiber coupling losses are calibrated out. An equivalent level of power could be obtained when pump is launched from the other side of the laser, considering the symmetry of the cavity. Using linear curve fitting, the single-sided slope efficiencies for the DFB and DBR lasers were found to be 14% and 23%, with laser thresholds of 96 mW and 65 mW at 1612-nm pumping. The peak laser wavelengths with up to 2W on-chip pump power for the DFB and DBR lasers were recorded by the spectrum analyzer, as shown in Fig. 5.18(c) and (d) respectively. Single-mode operation was enabled by the narrow bandwidth grating. The side-mode suppression ratio reached more than 70 dB.
Fig. 5.17(a) Measurement setup: a 1612 nm laser source together with a high-power EDFA, followed by a polarization controller to ensure that the fundamental TE mode is coupled into the gain waveguide of the laser. An optical spectrum analyser is used to capture the spectrum; (b) Output spectrum of DFB lasers with different grating periods, showing single-mode lasing at 1820 nm, 1840 nm, 1860 nm, 1880 nm, 1900 nm, and 1950 nm.
Fig. 5.18(a) DFB and (b) DBR laser output curves, showing 14% and 23% slope efficiency, 267 mW and 387 mW maximum output power, and 96 mW and 65 mW lasing threshold, respectively. The output spectra of (c) DFB and (d) DBR lasers at 1861 nm and 1881 nm, respectively, obtained with up to 2W on-chip pump power and showing side-mode suppression ratios $>$70 dB.

5.2.3 Erbium & thulium co-doped lasers

In this section, the lasers based on erbium-thulium co-doped film have also been investigated. As we pump erbium ion at 1.48 μm, there is energy transfer from $^4I_{13/2}$ (Er$^{3+}$) into thulium ion to excite the electron to $^3F_4$ (Tm$^{3+}$), so that thulium can have emission near 1.9 μm. The mechanism is shown in Fig. 5.19 below. The co-doping not only provides an alternative pumping scheme at erbium absorption wavelength (0.98 μm or 1.48 μm) for thulium emission, but also extends the emission of Er$^{3+}$ from
1.4-1.6 µm up to 2.0 µm.

Fig. 5.19 The energy diagram of Er\(^{3+}\)/Tm\(^{3+}\) co-doped film, showing energy transfer from Er\(^{3+}\) to Tm\(^{3+}\) to achieve emission around 1.9 µm.

The Er\(^{3+}\)/Tm\(^{3+}\) co-doped film is deposited at the top of the same DFB and DBR cavity structure as described in section 5.2. The film thickness is 1.22 µm. The Er\(^{3+}\) and Tm\(^{3+}\) doping concentration are measured to be \(1.97 \times 10^{20}\) and \(7.12 \times 10^{20}\) respectively through RBS. During the deposition, the Er target was mounted on a RF gun with 10 W target power, and Tm target was mounted on a DC gun with 12 W target power.

Fig. 5.20(a) shows the lasing spectrum from 1837 nm to 1968 nm with different grating periods. The uniform lasing power with >50 dB SMSR across the thulium gain spectrum is obtained. The lasing slope efficiency and threshold measurement results are shown in Fig. 5.20(b) and (c) below. After linear curve fitting of experimental data, the laser slope efficiency is measured to be 1.3% with respect to on-chip pump power, and 2.25% with respect to absorbed pump power. The lasing threshold is measured to be 500 mW with respect to on-chip pump power, and 100 mW with respect to absorbed pump power. Compared to pure Tm\(^{3+}\) doped laser slope efficiency, the Er\(^{3+}\)/Tm\(^{3+}\) co-doped laser has lower slope efficiency mainly contributed by the conversion efficiency of energy transfer from erbium ion \(^{4}I_{13/2}\) (Er\(^{3+}\)) into thulium ion \(^{3}F_{4}\) (Tm\(^{3+}\)).
Fig. 5.20 (a) Lasing spectrum from 1837 nm to 1968 nm with different grating periods, showing uniform lasing power with >50 dB SMSR across the thulium gain spectrum; (b) Slope efficiency measurement with respect to on-chip pump power, showing 1.3 % slope efficiency and 500 mW lasing threshold; (c) Slope efficiency measurement with respect to absorbed pump power, showing 2.25 % slope efficiency and 100 mW lasing threshold.

5.2.4 Summary

In summary, we have designed, fabricated and characterized high-power thulium DFB and DBR lasers integrated on a silicon chip. A CMOS-compatible segmented Si$_3$N$_4$ rib-waveguide was used to form the laser cavity. Gratings were added on both sides of the segmented Si$_3$N$_4$ rib waveguide to provide feedback and thulium-doped Al$_2$O$_3$ glass was used as the gain medium. By varying the grating period, single-mode lasers with wavelengths from 1800 nm to 1950 nm have been demonstrated within the thulium gain bandwidth. The highest DFB and DBR output powers of 267 mW and 387 mW under 1612 nm pumping were measured at...
1861 nm and 1881 nm wavelengths, with slope efficiencies of 14% and 23%, respectively. More than 70 dB side-mode suppression, which enables high signal-to-noise ratio for chip-scale communication and spectroscopic applications, was observed. In addition, the lasers with same DFB and DBR structure and Er$^{3+}$/Tm$^{3+}$ co-doped film as gain medium are demonstrated. Lasing with >50 dB SMSR is obtained across the gain spectrum of thulium, pumped at erbium absorption peak (1480 nm). 2.2% slope efficiency and 100 mW lasing threshold with respect to absorbed pump power are reported.
Chapter 6. Broadband 2-µm Emission on Silicon Chips:

Monolithically Integrated Holmium Lasers

Wavelengths in the region of around 2.0 µm have many transmission windows for atmospheric gases, strong water absorption, and highly efficient mid-infrared (IR) frequency conversions. Hence, laser sources at these wavelengths enable a wide range of applications in the fields of medicine, light detection and ranging (LIDAR) systems, remote sensing, trace-gas detection, and mid-IR wavelength generation [120, 150, 151]. Thulium-doped waveguide lasers operate efficiently around 1.9 µm [135, 149], but their efficiency at longer wavelengths is significantly reduced because of the diminishing emission cross-section of thulium-doped gain medium. In comparison, holmium-doped lasers have an emission spectrum spanning from 1.95 to 2.15 µm, allowing for signal generation in this longer wavelength range [152-154]. Furthermore, holmium-doped lasers have the potential to be in-band pumped using mature thulium laser technology [153].

Silicon photonics is a promising technology that has enabled production of large-scale devices [4], ultralow power modulators [5], and monolithically integrated lasers [19, 79, 155, 156] on a single chip with a low cost and compact size. In particular, integrated lasers beyond 2.0 µm are in demand due to the diminishing two-photon absorption of silicon [157, 158] while also providing a new communication band for integrated systems [120]. Rare-earth-ion-based monolithic lasers integrated on a silicon platform have been demonstrated at 1.0, 1.5 and 1.9 µm wavelengths using ytterbium [21, 159], erbium [18, 20, 79] and thulium [19, 81] doped Al₂O₃ glass as gain medium, respectively. However, to the best of our knowledge, monolithic integrated lasers beyond the 2 µm region have been minimally explored with no known demonstration of a holmium laser on a silicon photonics platform.

In this section, we demonstrate a holmium-doped distributed feedback (DFB) laser fabricated on a wafer-scale silicon photonics platform. The Al₂O₃:Ho³⁺ glass with broadband emission around 2 µm is used as gain medium. We achieve single-mode lasing at wavelength longer than 2.02 µm with a side-mode suppression ratio in excess of 50 dB. The maximum on-chip lasing power is 15 mW with a slope efficiency of 2.3%. In addition, lasing wavelength control within
the gain bandwidth of Al$_2$O$_3$:Ho$^{3+}$ film is demonstrated by changing the gain film thickness. This is, to the best of our knowledge, the first holmium-doped integrated laser demonstrated on a CMOS-compatible silicon photonics platform.

6.1 Device design and simulation

The waveguide cross-section of the DFB laser is shown in Fig. 6.1(a). A wavelength-insensitive waveguide design is used, which exhibits a high confinement factor in the gain material for an octave-spanning range across near-IR wavelengths (950-2000 nm) [40]. The octave-spanning range enables the waveguide structure to be used for a broad selection of pump and lasing wavelength. It consists of five Si$_3$N$_4$ bars buried under SiO$_2$ with a layer of Al$_2$O$_3$:Ho$^{3+}$ deposited on top. The thickness of each Si$_3$N$_4$ bar is 200 nm, and the oxide gap between this Si$_3$N$_4$ layer and the Al$_2$O$_3$ layer is 200 nm. The width and separation of the Si$_3$N$_4$ bars are optimized to be 300 nm and 350 nm, respectively, to provide high mode confinements for both pump (1.95 μm) and signal modes (~2.10 μm) within the Al$_2$O$_3$:Ho$^{3+}$ film. Using a vector finite-difference 2D eigenmode solver, the confinement factors within the holmium-doped gain region for pump and signal are calculated to be 85% and 83%, respectively.

The refractive indices of the materials used in our laser design are listed in Fig. 6.1(b). At both pump and signal wavelength, the refractive indices are sufficiently close that the material dispersion is negligible and excluded from the calculations. The guided modes in waveguides and the effective indices are calculated by vector finite-difference 2D eigenmode solver, with a discretization of 20 nm. The code is written in Matlab, and it solves the wave equation of the transverse electric field. After solving the eigen problem, the square of propagation constant $\beta^2$ can be obtained as eigenvalue, and hence the effective index was calculated using $n_{\text{eff}} = \beta \lambda / 2 \pi$. The transverse-electric (TE) field intensity of the fundamental mode at the pump and signal wavelengths is shown in Fig. 6.1(c).

A perspective view of the DFB laser is illustrated in Fig. 6.1(d) showing the perturbations on the side of the waveguide to form the laser cavity. The lateral gap
between the grating and waveguide is designed to be 450 nm, and the grating width is chosen to be 260 nm in order to provide enough feedback at the designed laser wavelength. The coupling coefficient ($\kappa$) of Bragg grating is calculated to be $1.10 \times 10^3$ m$^{-1}$, by substituting the calculated $\beta$ from mode solver into the following Eq. [101]:

$$\kappa = \frac{k^2}{2\pi\beta} (n_{Si3N4}^2 - n_{SiO2}^2) \sin(\pi D)\tau$$

where $D$ is grating duty cycle, which is equal to 0.5, $\tau$ is the mode overlap within the grating region, which is calculated to be 0.21%, $k$ is the wave number. The refractive index of $n_{Si3N4}$ and $n_{SiO2}$ are provided in Fig. 6.1(b). The total length of the cavity is 2 cm, which is limited by the length of the chip from fabrication facility. For a laser cavity length shorter than 2 cm, with the same pump power, the lasing power decreases. The mask space available for holmium doped lasers on this fabrication run was limited to 2 cm×0.05 cm. With a larger area available, a longer laser cavity (>2 cm) can be designed using a spiral geometry [32] for higher gain and better laser performance in terms of slope efficiency, output power and lasing threshold. The effective index ($n_{eff}$) of the waveguide is calculated to be 1.552 at 2100 nm, considering the grating as perturbations on both sides of the segmented Si$_3$N$_4$-rib to provide feedback. Therefore, the grating period ($\Lambda$) can be calculated using:

$$\Lambda = \frac{\lambda}{2n_{eff}}$$

where $\lambda$ is the designed laser wavelength. Based on the $n_{eff}$ from 2D mode solver and $\kappa$ obtained from Eq. (1) above, the transmission response of our DFB cavity, as shown in Fig. 6.1(e), is calculated by using the transfer matrix of grating [101]. A quarter-wave phase shift is introduced in the middle of the simulated section, with $\kappa$ reversing sign: $\kappa = -\kappa$. 

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Fig. 6.1(a) Cross-sectional view of the laser waveguide including five strips of Si$_3$N$_4$, an Al$_2$O$_3$:Ho$^{3+}$ film, SiO$_2$ and air as a lower and upper cladding, respectively on Si substrate. (b) Refractive indices of the waveguide materials. (c) Transverse-electric (TE) field intensity for the fundamental mode at the pump (1950 nm) and laser output (2100 nm) wavelengths in the DFB waveguide. (d) 3D illustration of the DFB laser showing the different material layers and cavity features (not to scale). (e) Calculated transmission of designed DFB cavity at 2100 nm.

6.2 Device fabrication

The lasers were fabricated in a state-of-the-art CMOS foundry on a 300-mm silicon wafer. The wafer-scale fabrication process before the Al$_2$O$_3$:Ho$^{3+}$ film deposition is the same as that which has been reported earlier [81]. After dicing the wafer into small identical chips, a 1.14-µm-thick Al$_2$O$_3$:Ho$^{3+}$ film was deposited on one of the chips via
reactive co-sputtering as a back-end-of-line process. The doped Al$_2$O$_3$ film was reactively co-sputtered from 2-inch diameter metallic aluminum and holmium targets in a confocal arrangement. The reaction was within an argon and oxygen atmosphere. The deposition system (AJA ATC Orion 5), as shown in Fig. 6.2(a) below, is equipped with two radio frequency (RF) magnetron sputtering guns. The power setting on the aluminum and holmium sputtering guns were 200 W and 18 W, respectively. The deposition was carried out at a constant pressure of 3 mTorr. The argon flow rate was kept at constant flow of 11.0 sccm, and the oxygen flow rate was adjusted from 1.1 to 1.6 sccm in order to maintain the oxygen flow – bias voltage curve at the “knee” point of the hysteresis point [160] during the entire deposition process. At this point, the film deposited is stoichiometric, while the oxygen flow is maintained below the point where the bias voltage of aluminum target and deposition rate start to drop. The substrate temperature was measured to be 415 °C. Deposition runs with different Ho$^{3+}$ doping levels revealed that a measured Ho$^{3+}$ doping concentration of $3.2 \times 10^{20}$ cm$^{-3}$, through Rutherford backscattering spectrometry (RBS) analysis, provides the best lasing performance. Given the same pump power, a lower doping concentration will suffer from lower gain while higher doping concentration will result in ion clustering or quenching [84, 86, 161]. In addition, the propagation loss of the passive Al$_2$O$_3$ film (without doping) deposited on a thermally oxidized silicon substrate was measured using the prism coupling method. The propagation loss of the Al$_2$O$_3$ film was found to be < 0.1 dB/cm.

A scanning electron microscopy (SEM) image of Si$_3$N$_4$ layer is illustrated in Fig. 6.2(b). In order to remove the top SiO$_2$ cladding layer for SEM imaging, prior to Al$_2$O$_3$ deposition, the device was placed into buffered hydrogen fluoride (HF) for 140 s and coated with 5 nm thin gold layer at top to avoid charging.
Fig. 6.2(a) Schematic diagram of reactive sputtering deposition system: two guns with RF power supply are mounted at the top of the chamber. Ar\textsuperscript{3+} ions are accelerated to bombard the Al and Ho targets. O\textsubscript{2} is supplied for reaction. The Al\textsubscript{2}O\textsubscript{3}:Ho\textsuperscript{3+} film is formed on substrate, which is heated up by heater from bottom of the chamber. (b) SEM image of the Si\textsubscript{3}N\textsubscript{4} pattern (top view) after removing SiO\textsubscript{2} top cladding by hydrogen fluoride (HF) etching.

6.3 Laser characterization

The common pumping scheme of holmium is shown in Fig. 6.3(a). For direct pumping of singly-doped holmium, the absorption bands of interest lie at wavelengths of 1.15 μm (\(^4\)I\(_7\) level) and 1.95 μm (\(^5\)I\(_7\) level). Pumping of the \(^4\)I\(_7\) level can be addressed by 1.12 μm laser diodes [154] or long wavelength operation of ytterbium fiber lasers [162]. However, the low quantum efficiency of this pumping scheme limits its efficiency and power scaling potential. Alternatively, the \(^5\)I\(_7\) level can be accessed by thulium fiber or on-chip lasers, which can provide a high-power pump source at 1.95 μm.

The measurement setup for characterization of the lasers is illustrated in Fig. 6.3(b). A high-power fiber laser source at 1950 nm was used for optical pumping. A polarization controller was used to ensure that the pump light is coupled into the fundamental TE mode of the gain waveguide. A cleaved single-mode SM-2000 fiber
was used to butt-couple the pump light onto the chip, and another cleaved single-mode SM-2000 fiber was used to butt-couple the output signal of the laser from the chip. The setup and fiber-to-chip coupling losses were first determined using a 3-mm-long passive waveguide, which had an undoped Al₂O₃ film at top but was otherwise identical to the laser gain waveguide, and SM-2000 fibers on each side of the chip for both pump and lasing wavelengths. The fiber-to-chip coupling losses for SM-2000 were measured to be 7.5 dB at the pump wavelength, and 6.9 dB at the laser output wavelength. The output signal was coupled into an optical spectrum analyzer (Yokogawa AQ6375) to capture the spectrum.

![Diagram](image)

Fig. 6.3(a) 3-level holmium laser energy diagram showing pump and laser transitions. (b) The measurement setup, which contained a high-power 1950 nm thulium fiber laser as pump source, a polarization controller for efficient coupling, and an optical spectrum analyzer to capture the output spectrum. Cleaved fibers are used to butt couple pump and signal onto or from the chip.
First, we compare the spontaneous emission spectra of thulium- and holmium-doped Al$_2$O$_3$ films, which both emit near 2 µm. We deposited Al$_2$O$_3$:Tm$^{3+}$ and Al$_2$O$_3$:Ho$^{3+}$ films on top of the Si$_3$N$_4$ waveguide design illustrated in Fig. 6.1(a). A low power pump at 1.614 µm (at the Tm$^{3+}$ absorption peak) was used to generate spontaneous emission in the Al$_2$O$_3$:Tm$^{3+}$ waveguide on the $^3F_4 \rightarrow ^3H_6$ transition. The spectrum recorded by an optical spectrum analyzer is shown in Fig. 6.4(a). It shows that the emission range is from 1680 nm up to 2020 nm, with 3-dB bandwidth of 340 nm. Lasing within this emission range has been reported by using the same Al$_2$O$_3$:Tm$^{3+}$ thin film and varying the grating period [81], as mentioned in previous chapter. In comparison, the spontaneous emission spectrum of the Al$_2$O$_3$:Ho$^{3+}$ film is shown in Fig. 6.4(b). A low power laser source at 1.12 µm is used as the pump. The emission range has a 3-dB bandwidth of 200 nm, spanning from 1930 nm up to 2130 nm, which is beyond the upper limit of the Al$_2$O$_3$:Tm$^{3+}$ emission. Lasing within this emission range is achieved by varying the grating period as well as Al$_2$O$_3$ thin film thickness, as shown in the following parts of this article.

To demonstrate lasing using Al$_2$O$_3$:Ho$^{3+}$ as a gain medium, two DFB lasers with different grating periods were fabricated. The two grating periods were 659 nm and 677 nm, which based on Eq. (2), correspond to wavelengths around 2051 nm and 2101 nm, respectively. The measured optical spectra of the corresponding DFB laser designs are shown in Fig. 6.5(a) and (b). Due to the narrow reflection bandwidth of the DFB structure, single-mode operation is demonstrated and more than 50 dB side-mode
suppression ratio is achieved for both designs. A 50 pm (~3.4 GHz) optical spectrum analyzer resolution used in the experiment confirms the single mode operation of the laser with ~5 GHz free spectral range. Within the broad gain bandwidth of Al$_2$O$_3$:Ho$^{3+}$, we are able to control the laser wavelength by choosing a proper grating period based on Eq. (2).

![Graph](image)

Fig. 6.5 The output spectra of the DFB lasers at (a) 2051 nm and (b) 2101 nm obtained with up to 800 mW on-chip pump power, showing side-mode suppression ratios >50 dB.

![Graph](image)

Fig. 6.6(a) DFB laser output power with respect to on-chip pump power: showing 2% slope efficiency, 130 mW lasing threshold and 15 mW maximum output power; (b) DFB laser output power with respect to absorbed pump power near the lasing threshold: showing 50 mW lasing threshold and 2.3% slope efficiency.

The device that operates at the higher emission cross-section of the holmium gain spectrum, which is 2050 nm, was selected for the lasing slope efficiency measurement shown
in Fig. 6.6. The maximum on-chip output power of the DFB laser was measured to be 15 mW, limited by the on-chip pump power of 800 mW. The output power was measured from a single side of the laser and the fiber-to-chip coupling loss was calibrated out. An equivalent level of power can be obtained if the pump is launched from the other side of the laser due to the symmetry of the cavity design. Using linear curve fitting to the experimental data, we demonstrate a single-sided slope efficiency of 2.0% and a laser threshold of 130 mW with 1950 nm pumping. In order to find the effective lasing threshold with respect to absorbed pump power, the residual pump power was measured near the lasing threshold of the same device. The absorbed pump power is obtained by subtracting the measured residual pump from the on-chip pump power. The laser power near the threshold with respect to absorbed pump power is shown in Fig. 6.6(b). The lasing threshold with respect to absorbed pump power is found to be 50 mW, and the slope efficiency is measured to be 2.3%, after linear curve fitting of experimental data. The slope efficiency reported here is limited by the loss in the laser cavity, which is mainly attributed to the waveguide surface roughness and loss from the materials (Si₃N₄, Al₂O₃, SiO₂). The loss of the laser cavity can be reduced by improving fabrication process (e.g., using LPCVD instead of PECVD Si₃N₄). In addition, the laser performance in terms of slope efficiency, output power and lasing threshold can be improved by using a distributed-phase-shifted (DPS)-DFB with optimized grating coupling coefficient (κ) instead of a quarter-wave phase shift (QPS)-DFB [40]. The improvement of the DPS-DFB cavity can be attributed to the reduction of spatial hole burning in QPS-DFB cavity and a longer effective gain section.

6.4 Lasing wavelength shift by changing Al₂O₃:Ho³⁺ film thickness

Since the deposition of the Al₂O₃:Ho³⁺ thin film is a back-end-of-line process, the lasing wavelength of our DFB laser can be controlled by changing the thickness of the film. Using the same Si₃N₄ grating periods (659 nm and 677 nm), the thickness of the film is reduced from 1.14 μm to 0.91 μm by reducing the sputtering time in a new Al₂O₃:Ho³⁺ deposition run. The lasing wavelength is shifted from 2050.2 nm to 2022.7 nm and
2101.4 nm to 2072.6 nm, respectively, as shown in Fig. 6.7(a) below. In addition, the effective index of the gain waveguide with reduced $\text{Al}_2\text{O}_3:\text{Ho}^{3+}$ film thickness is calculated using the 2D eigenmode solver, and hence the expected lasing wavelengths are calculated by substituting the $n_{\text{eff}}$ and grating period into Eq. (2). A comparison of the calculated lasing wavelength from simulation and the measured lasing wavelength from the experiment is shown in Fig. 6.7(b). They agree to an accuracy of 1 nm. The difference may be caused by fabrication variation of the $\text{Si}_3\text{N}_4$ layer, as well as by the $\text{Al}_2\text{O}_3:\text{Ho}^{3+}$ film thickness non-uniformity along the 2-cm-long DFB cavity [78]. In addition, the thermal shift of the device, which was reported to be 0.02 nm/°C [38], may also have an effect.

Lasing was observed with film thicknesses ranging from 0.85 μm up to 1.25 μm. If the film thickness is less than 0.85 μm, the laser device experiences low gain. This is due to the fact that as the film gets thinner, the pump and signal mode overlap decreases, and therefore the gain decreases. Meanwhile, if the film thickness is more than 1.25 μm, the laser device experiences high round-trip loss. This is mainly due to the fact that as the film gets thicker, the horizontal mode confinement (provided by $\text{Si}_3\text{N}_4$ bars) is weaker and hence the expanded mode will experience more scattering loss. Additionally, with a gain film thickness in the range of 0.85 μm to 1.25 μm, there is an optimum thickness value to provide the highest net gain giving the best laser performance in terms of output power, slope efficiency and lasing threshold.
Fig. 6.7 (a) Demonstration of lasing wavelength control by changing the gain film thickness. (b) Comparison of calculated lasing wavelength from simulation and real lasing wavelength from experiment.

### 6.6 Summary

In summary, we have designed, fabricated and characterized holmium doped DFB lasers monolithically integrated on a silicon chip. The holmium-doped Al₂O₃ glass, which provides broadband emission from 1930 nm to 2130 nm, was used as gain medium. A CMOS-compatible segmented Si₃N₄ rib-waveguide was used to form the laser cavity. Gratings were added on both sides of the segmented Si₃N₄ rib waveguide to provide feedback. By varying the grating period, we demonstrated single-mode lasers with wavelengths at 2051 nm and 2101 nm, which are within the holmium gain bandwidth. By changing the Al₂O₃:Ho³⁺ film thickness, the lasing wavelength can be controlled. With 1950 nm pumping, a laser output power of 15 mW was measured at a wavelength of 2050 nm with a slope efficiency of 2% and greater than 50
dB side-mode suppression ratio. This demonstration represents an important step toward high-performance on-chip silicon-based laser sources for the 2 to 2.2 µm wavelength range.
Chapter 7. System Level Integration for Optical Communication

From chapter 3 to 5, we discussed rare-earth-doped lasers based on different dopants. In this chapter, we will focus on the system level integration of the erbium doped laser. As erbium has emission at the current communication wavelength, the system level integration presented here is for optical communication. The chapter includes two parts. The first part (7.1) presents a monolithically integrated WDM light source by cascading DFBs in a silicon photonics platform. The second part (7.2) demonstrates an athermal synchronization of a DFB laser with a WDM filter due to the similar thermal response of DFB laser and silicon nitride devices. It also shows good thermal stability of the DFB laser contributed by the low thermo-optic coefficient of Al₂O₃.

7.1 WDM light source monolithically integrated on a silicon photonics platform

A wavelength division multiplexed (WDM) light source is a key component in silicon photonics technology for application in optical communications [2, 163, 164]. It generally consists of several uniformly spaced optical wavelengths that can be used to encode multiple communication channels in a common output. Several research groups have demonstrated integrated WDM light sources of up to 16 channels by bonding of III-V gain material onto the silicon chip [102, 103, 114, 165, 166]. However, these hybrid devices often require careful temperature control and complex fabrication steps with yield challenges. Alternatively, rare earth doped glass lasers on silicon, such as erbium-doped aluminum oxide (Al₂O₃:Er³⁺) or thulium-doped aluminum oxide (Al₂O₃:Tm³⁺) lasers, have been shown to achieve high power, low noise, good thermal stability, and low lasing threshold [19, 37, 81, 148, 167]. Monolithic integration of Al₂O₃: Er³⁺ lasers has been demonstrated in a CMOS-compatible process with only a single backend Al₂O₃:Er³⁺ deposition step [18, 20, 117]. The wide gain bandwidth of the erbium enables the laser wavelength tunability and design flexibility [7, 27, 28, 31, 34, 43]. By
combining several lasers with varying grating periods, a multi-wavelength light source can be obtained with custom longitudinal mode spacing.

In this section, we demonstrate a monolithic WDM source by cascading four Al₂O₃:Er³⁺ DFB lasers. We achieve simultaneous operation of four DFBs at a total power of -10.9 dBm and an average side-mode suppression ratio (SMSR) of 38.1 ± 2.5 dB in each DFB. The measured temperature dependent wavelength shift is uniform across all four lasers with \( d\lambda/dT = 0.02 \text{ nm/°C} \).

### 7.1.1 Device design

The design of the cascaded-DFB structure is shown in Fig. 7.1. Four DFB lasers are cascaded in series with the length of each laser \( L_{\text{DFB}} = 5.5 \text{ mm} \), distance between each laser \( L_{\text{spacing}} = 0.1 \text{ mm} \), and first grating period \( \Lambda_1 = 490 \text{ nm} \) with 2 nm-subsequent increment (\( \Lambda_2 = 492 \text{ nm}, \Lambda_3 = 494 \text{ nm}, \text{ and } \Lambda_4 = 496 \text{ nm} \)). Each DFB laser has a quarter phase shift located at the center, thus emitting symmetric outputs on both sides. The right output from DFB₁ propagates to the next laser DFB₂, and so on to the right end of the structure. The combined output is then a WDM of four uniformly spaced wavelengths. In order to design an asymmetric output that emits on only one end of the device, the phase shift can be placed to be slightly off-centered in the cavity. With small reabsorption loss (0.5 dB/cm at 1563 nm [119]) and good thermal stability of the Al₂O₃: Er³⁺ laser, the lasers can be placed closely with negligible cross talk.

![Fig. 7.1 Design of WDM light source by cascaded DFBs. Four Al₂O₃: Er³⁺ DFB lasers at uniformly spaced grating period are cascaded in series to generate multi-wavelengths laser output.](image)

In order to allow integration into a more general silicon photonics wafer-scale process where thicker, higher-confinement silicon nitride (SiNₓ) structures might be preferred [96], we
extend our erbium laser design [148] to work for a thicker SiN by using a multi-segmented waveguide structure [32, 95]. To form a compact CMOS compatible cascaded-DFB structure, we optimized the multi-segmented waveguide design for short lasers. Fig. 7.2 shows the laser waveguide which consists of nitride (SiN) segments with the grating perturbation formed by periodic etching of the first and last segments. The SiN segments have dimensions of thickness \( t = 200 \text{ nm} \), width \( w = 450 \text{ nm} \), and gap \( g = 400 \text{ nm} \). A silicon dioxide (SiO\(_2\)) gap \( g_{ox} = 200 \text{ nm} \) is then added on top of the SiN structure. All fabrication steps until SiO2 cladding are completed in a 300 mm line CMOS foundry, as reported earlier [148] only with difference in layer thickness. Lastly, the Al\(_2\)O\(_3\): Er\(^{3+}\) gain medium of thickness \( t_{AlO} = 1100 \text{ nm} \) is deposited by a reactive co-sputtering process [119, 168] as the final backend step. We use the prism coupling method to estimate the Al\(_2\)O\(_3\):Er\(^{3+}\) gain film background loss of <0.1 dB/cm and dopant concentration of \( 1.0 \times 10^{20} \text{ cm}^{-3} \) by linear fitting of measured total film loss (\( \alpha_{tot} \)) vs. the film absorption cross-section (\( \sigma_a \)) around 1550 nm, as covered in section 4.1.1.

The multi-segmented waveguide is designed to have a single transverse-electric (TE) mode at the pump (980 nm) and laser (1550 nm) wavelengths. The design also allows for efficient optical pumping of the Al\(_2\)O\(_3\): Er\(^{3+}\) lasers with high mode confinement and good intensity overlap of the pump and laser mode. The confinement factor of the pump and laser in the gain layer is calculated using a finite difference mode-solver to be 89% and 90% respectively, with intensity overlap >95%, as shown in Fig. 7.3.

![Diagram of CMOS-compatible multi-segmented waveguide design of Al\(_2\)O\(_3\):Er\(^{3+}\) DFB lasers.](image)

Fig. 7.2 CMOS-compatible multi-segmented waveguide design of Al\(_2\)O\(_3\):Er\(^{3+}\) DFB lasers. The structure consists of five SiN segments used for thicker SiN design, with the grating constructed by periodic perturbation of the outer segments.
Fig. 7.3 Mode-solver calculation of the intensity distribution for the pump (980 nm) and laser (1550 nm) wavelengths in the multi-segmented waveguide design.

7.1.2 Device characterization

We measure the transmission response of the cascaded-DFB structure by using a tunable laser, as shown in Fig. 7.4. Sharp resonances are located at the center of each DFB response at wavelengths $\lambda_1 = 1563.56$ nm, $\lambda_2 = 1569.84$ nm, $\lambda_3 = 1575.90$ nm, and $\lambda_4 = 1581.76$ nm. The sharp peaks have lower transmission amplitude (10-15 dB) in the passive measurement of $\text{Al}_2\text{O}_3: \text{Er}^{3+}$ mainly due to absorption of un-pumped active ion. The wavelength spacings between adjacent DFBs are slightly non-uniform ($\Delta\lambda_{\text{adjacent}} = 6.28$ nm, 6.06 nm, and 5.86 nm). We believe that this can be explained by the thickness non-uniformity of the $\text{Al}_2\text{O}_3: \text{Er}^{3+}$ film deposition. In a standard sputtering system, the target is mounted on a rotating platform with radially varying thickness profile from the center. Thus, a conventional straight DFB structure would experience thickness non-uniformity along the cavity. We present a more detailed explanation and a possible solution in a follow-up work [62] as well as section 2.5 in this thesis.

Laser measurements were carried out by pumping the cascaded-DFB structure from both sides with two fiber pigtailed laser diodes centered at 978 nm (left side) and 976 nm (right side). Accounting for fiber-chip coupling losses, the maximum on-chip pump powers of the 978 nm and 976 nm diodes are estimated to be 120 mW (left pump) and 70 mW (right pump) respectively. The output is monitored using two optical spectrum analyzers (OSA) on both sides. We obtain laser wavelengths centered at 1563.92 nm, 1570.20 nm, 1576.28 nm, and
1582.16 nm, slightly higher than the passive transmission measurement due to local heating by pump absorption. The peak output powers obtained in the left (and right) OSA for the four DFBs are as follows: $-17.7 \text{ dBm} \ (\text{-17.4 dBm})$, $-20.4 \text{ dBm} \ (\text{-20.2 dBm})$, $-22.1 \text{ dBm} \ (\text{-22.6 dBm})$, $-19.1 \text{ dBm} \ (\text{-24.0 dBm})$. The measured power from the left and right OSA generally show similar output levels, except for DFB$_4$, which might be caused by fabrication defect. We plot the total emission spectrum of the cascaded DFBs by adding the spectrum obtained from both left and right OSA in Fig. 7.5. The total peak power obtained for different wavelengths are $-14.5 \text{ dBm}$, $-17.5 \text{ dBm}$, $-19.4 \text{ dBm}$, and $-18.0 \text{ dBm}$. This corresponds to a total cascaded DFB output power of $-10.9 \text{ dBm}$ from all four DFBs, an average of $-16.9 \text{ dBm}$ per DFB. By assuming the noise floor at $-55.0 \text{ dBm}$ as shown in figure, we obtain an average of $38.1 \pm 2.5 \text{ dB SMSR}$ per DFB, which is to our knowledge, one of the best signal to noise performances of an on-chip WDM light source ever reported [103].

![Fig. 7.4 Transmission measurement of cascaded-DFB structure. The sharp peaks have lower transmission amplitude (10-15 dB) in the passive measurement of Al$_2$O$_3$:Er$^{3+}$ mainly due to absorption of un-pumped active ion.](image)
We perform a temperature dependence test of the cascaded DFBs by placing the chip on a thermoelectric cooler (TEC). The TEC temperature can be adjusted from 20 to 40 °C by varying the current level. Fig. 7.6 shows the spectrum of DFB$_1$ at temperatures of 20, 30, and 40 °C. No significant change of the output power is observed at varying temperatures, demonstrating thermal stability of the Al$_2$O$_3$:Er$^{3+}$ lasers. Fig. 7.7 shows the wavelengths of all four DFBs at varying temperature with an uniform temperature-dependent shift of $d\lambda/dT = 0.02$ nm/°C across all four lasers. This is less than half compared with the thermal wavelength shift of the hybrid lasers for WDM [102-105].
Fig. 7.6 OSA spectra of DFB₁ laser at varying temperatures from 20 to 40 °C, showing $d\lambda/dT$ of 0.02 nm/°C

Fig. 7.7 Temperature dependent wavelength shift of lasers in cascaded-DFB structure shows gradual changes in 20 – 40 °C (0.02 nm/°C) and uniformity across all channels

Improved performance of the cascaded DFB laser WDM light source can be achieved in the following ways. The maximal output of each DFB laser can be optimized by varying the grating strength $\kappa$ and cavity length $L_{DFB}$, as shown in [20]. The pump laser can be recirculated
by using a selective reflector to obtain a more flattened spatial pump profile. In addition, by taking into account the doping concentration, reabsorption loss, and total available pump power, the combined WDM output can be carefully designed to have better power uniformity. Lastly, to scale the cascaded-DFB to include more DFB lasers, several structures can be combined in parallel or the structure can be folded around the chip to increase the total available length (here the design was constrained by the chip length of 2.5 cm).

7.1.3 Summary

In summary, we have demonstrated CMOS-compatible monolithic integration of a WDM light source in a silicon photonics platform by cascade of Al₂O₃: Er³⁺ DFB lasers. Simultaneous operation of four DFB lasers has been achieved with a total power of −10.9 dBm, corresponding to an average power of −16.9 dBm and a 38.1 ± 2.5 dB SMSR for each DFB laser. The output shows good thermal stability with varying chip temperatures (20–40 °C), with a uniform temperature dependent wavelength shift of $d\lambda/dT = 0.02$ nm/°C across all four DFBs. We propose that such Al₂O₃: Er³⁺ lasers are an alternative approach to low noise and thermally stable WDM light sources for optical communications.

7.2 Athermal synchronization of laser source with WDM filter on a silicon photonics platform

With an increasing demand for data communication bandwidth, integrated silicon photonic technologies have been extensively studied to overcome the limits of electrical interconnects [169, 170]. In an optical interconnect circuit, microring resonators (MRRs) are commonly used as multiplexers/demultiplexers in wavelength division multiplexing (WDM) systems [171, 172]. However, to make the MRR and on-chip laser work together, the resonances of the MRRs should be matched to the laser wavelengths for all operating temperatures [173, 174]. Although the resonance wavelength of a MRR can be controlled by using thermal tuning [172, 175], the power consumption to align the wavelengths of many MRRs is significant in a high-channel count WDM system [172, 176]. Even when an athermal reference cavity is used, the laser has to be
electronically locked to it to prevent any thermally induced mismatch from downstream filters [177]. To overcome these problems, the MRR filter resonant wavelength can be matched to the laser wavelength and have the same thermal wavelength shift as the laser source [104, 105]. As a result, system-level temperature control-free operation can be achieved without the need for additional tuning power.

Prior to this work, on-chip lasers have been demonstrated using rare-earth elements doped in Al₂O₃ as gain media [18-21, 36, 83], which has proven to be effective. Compared to III-V material based systems [11], Si₃N₄ laser cavities utilizing rare-earth-doped Al₂O₃ can have a similar overall thermal response to other Si₃N₄ devices on the chip such as MRR filters [178]. This makes it possible to achieve a control-free operation WDM system consisting of a laser source and a wavelength filter over a wide temperature range.

Here we demonstrate an Al₂O₃:Er³⁺ based distributed feedback (DFB) laser cascaded with Si₃N₄ MRRs for filtering different WDM channels on the same chip. The low thermo-optic coefficient of Al₂O₃ and Si₃N₄ [179-182] and the comparable thermal shift of the effective index in the laser and microring cross-sections enable lasing and resonance wavelength synchronization over a wide range of temperatures. We achieve >15 dB power extinction ratio (between a matched laser-MRR channel and an unmatched channel) from 20 to 50 °C. The wavelength shifts of the laser and the MRRs are synchronized to 0.02nm/ °C, proving that the system is athermal. The athermal synchronization approach reported here is not limited to microring filters but can be applied to any Si₃N₄ filter with integrated lasers using rare earth ion doped Al₂O₃ as a gain medium to achieve system-level temperature control free operation.

7.2.1 Device design and fabrication

The waveguide cross-section of the DFB laser is shown in Fig. 7.8(a). The width and gap of the Si₃N₄ pieces are selected to be 600 nm and 400 nm, respectively, to provide high mode confinement for both the 1480 nm pump and 1550 nm laser modes within the Al₂O₃:Er³⁺ film. The confinement factors in the Al₂O₃:Er³⁺ film are calculated to be
84.05% and 84.86% for the fundamental transverse electric (TE) modes at the pump and laser wavelengths, respectively, using a finite-difference 2D mode solver. The height of each Si$_3$N$_4$ piece is 200 nm. The gap between the Si$_3$N$_4$ and Al$_2$O$_3$ layer is 200 nm. A 1100-nm thick Al$_2$O$_3$:Er$^{3+}$ film is deposited on top to provide gain. The DFB cavity is formed by adding Si$_3$N$_4$ grating pieces alongside the waveguide with a width of 400 nm, a gap of 500 nm, duty cycle of 0.5, and period of 487 nm. The coupling coefficient ($\kappa$) is calculated to be $6.4 \times 10^2$ m$^{-1}$. The total length of the DFB laser is 2 cm, limited by the maximum length of the chip. For a laser cavity length shorter than 2 cm, with the same pump power, the lasing power decreases. The coupling coefficient and cavity length product ($\kappa \cdot L$) is 12.8. At the end of the DFB, a transition is designed to adiabatically couple the mode from DFB gain waveguide into the mode of a double layer Si$_3$N$_4$ waveguide. After the transition, the double layer Si$_3$N$_4$ waveguide is connected to MRRs. The cross-section of the double layer Si$_3$N$_4$ MRR is shown in the right side of Fig. 7.8(a). The Si$_3$N$_4$ pieces in the MRR have a width of 1 μm, and a height of 200 nm for each layer, with a 100 nm oxide gap in between. The TE field intensity of the fundamental mode for a DFB gain waveguide and a Si$_3$N$_4$ MRR are shown in Fig. 7.8(b), which are calculated from a finite difference mode solver and a bend waveguide mode solver, respectively. The refractive indices used in mode solver are provided in Fig. 7.8(c). To ensure mode confinement within the Si$_3$N$_4$ MRRs, their diameters were selected to be around 90 μm, which corresponds to a free spectral range (FSR) of 5 nm. The entire device is illustrated in Fig. 7.8(d). Four MRRs after the DFB represent three types of filter channels: one matched, one adjacent, and two low-interfering channels. The diameters of the MRRs are chosen to be 90.02 μm, 90.10 μm, 90.18 μm and 90.26 μm in order to evenly distribute the resonances within one FSR. The drop ports of the MRRs are used to couple out the laser signal.
The device was fabricated using a 300 mm CMOS foundry. The fabrication process is illustrated in Fig. 7.9(a). First, a 6-µm thick SiO$_2$ bottom cladding layer is deposited on a 300mm silicon wafer via plasma-enhanced chemical vapor deposition (PECVD). Afterwards, a 200-nm thick PECVD Si$_3$N$_4$ layer is deposited, followed by a top surface polishing process to reduce the optical scattering loss (Step I). The Si$_3$N$_4$ layer is subsequently annealed at 1050 °C for 72 minutes to reduce absorption due to Si-H and N-H bonds around 1.52 µm. Then the Si$_3$N$_4$ layer is patterned using 193 nm immersion lithography and reactive ion etching (Step II). The side wall roughness is minimized by a short 900 °C wet oxidation, followed by an HF dip. Next, a 100-nm thick SiO$_2$ layer
is deposited and the top surface is flattened via chemical-mechanical planarization (CMP), as shown in Step III. Following that step, a second 200-nm-thick Si₃N₄ layer is deposited and patterned using the same method as the first layer (Step IV). The fabrication variation on the Si₃N₄ pattern will lead to MRR resonance shifts of up to 1 nm, but this has minimal effect on the DFB lasing wavelength due to the fact that most of the mode is confined in the Al₂O₃ film and that the fabrication variations only effect the duty cycle and not the grating period. Above the top Si₃N₄ layer, a 4-µm-thick SiO₂ layer is deposited. The fabrication of the MRRs is completed at Step V, but the DFB laser needs two additional steps. In Step VI, the top SiO₂ layer is patterned and a 4-µm-deep and 80-µm-wide gain trench is etched using the top Si₃N₄ layer as an etch stop. Finally, in Step VII, a 200-nm-thick SiO₂ layer is deposited within the laser trench and a 1110-nm-thick Al₂O₃:Er³⁺ thin film is deposited via reactive co-sputtering. The thickness of Al₂O₃:Er³⁺ film is chosen to ensure that the lasing wavelength matches with one of the Si₃N₄ MRR resonances. The deposition of Al₂O₃:Er³⁺ film is a single-step back-end-of-line process on the silicon wafer, allowing direct access to the laser design. Controlling the Al₂O₃:Er³⁺ thin film thickness can be used as a general approach to ensure the lasing wavelength matches with a single channel resonance. Precise control of the DFB lasing wavelength from different wafers has been demonstrated recently in thulium doped Al₂O₃ film [81]. Deposition runs with different doping levels reveals an optimum Er³⁺ doping concentration of 1.2×10²⁰ cm⁻³. Given the same pump power, a lower doping concentration will suffer from lower gain while a higher concentration will result in ion clustering or quenching [84, 85]. In order to visualize the Si₃N₄ patterning, the top SiO₂ cladding layer was etched. Scanning electron microscope (SEM) images of the Si₃N₄ patterns (top view) for the DFB laser and a MRR filter are displayed in Figs. 7.9(b) and (c), respectively.
The DFB laser and MRR fabrication steps including (I) deposition and (II) patterning of the bottom Si$_3$N$_4$ layer, (III) deposition and flattening of the SiO$_2$ cladding layer, (IV) deposition and patterning of the top Si$_3$N$_4$ layer, (V) deposition of the top SiO$_2$ cladding layer, (VI) patterning and etching of the top SiO$_2$ cladding to form a laser trench, and (VII) deposition of SiO$_2$ and Al$_2$O$_3$:Er$^{3+}$ within the laser trench. (b) (c) SEM image of Si$_3$N$_4$ pattern (top view) for the DFB laser and MRR after removing SiO$_2$ top cladding from Step III.

7.2.2 System characterization

To characterize the system, both external and internal laser measurements were performed on the device. Fig. 7.10(a) shows the setup of the measurement using an external laser, which includes a tunable laser source (Keysight 81600B) to sweep the
wavelength of the input signal, a polarization controller to ensure the input is coupled into the fundamental TE mode of the DFB and MRRs, an optical power meter to record the signals from the drop ports of the MRRs, shown in Figs. 7.10(b) and(c), and a thermoelectric cooler (TEC) to monitor and stabilize the operating temperature of the system with a feedback loop. A cleaved single-mode SMF-28 fiber is used on each side of the chip to butt-couple the tunable laser signal onto the chip, and butt-couple the output signal from the chip respectively.

Fig. 7.10(b) shows the passive response of each of the four MRR drop ports with an external tunable laser at 20 °C. The main peaks represent the TE resonances of the MRRs, and the smaller lobes on the right side of the peaks are the transverse magnetic (TM) resonance of the MRRs. The loaded quality factor of TE resonance is $2.2 \times 10^4$. The existence of the TM mode may be due to the fact that the waveguide after the DFB laser has an asymmetry in horizontal direction. Under the condition that the transition is not perfectly adiabatic, the TE mode couples into the TM mode. The polarization controller is tuned to couple into the fundamental TE mode of the DFB gain waveguide. For channel 1, only one TE mode peak is observed at 1539.9 nm. At 1544.4 nm, there is no TE mode peak in the system, indicating that the response of the MRR cancels with the DFB cavity response. From simulation, the MRR corresponding to channel 1 has a resonance at 1544.4 nm, and hence, the DFB lasing signal can have high transmission into this channel. For comparison, the passive response of the DFB cavity together with the MRR drop channels 2, 3, and 4 are shown in Fig. 7.10(b). For these channels, two orders of the TE resonance are observed instead of one. For channel 2 and 3, at the DFB cavity resonance wavelength of 1544.4 nm, the drop ports of the MRRs have low transmission because the channels are not matched. Therefore, these two channels are expected to have less power in the drop port when the on-chip laser with lasing wavelength of 1544.4 nm is on. While for channel 4, at 1544.4 nm, the transmission is not as low as channels 2 and 3 since it has a tail of the TM mode at this wavelength. Therefore, channel 4 will have a relatively higher output power for the input laser at 1544.4 nm. From Fig. 7.10(b) and using channel 2, 3, or 4, the FSR of the MRR is
measured to be 5 nm. The temperature of the system was then controlled using the TEC, and the passive responses of channel 1 at different temperatures was measured, as shown in Fig. 7.10(c). A wavelength shift of 0.2 nm is observed for a 10 °C temperature change within a temperature range from 20 to 50 °C. While beyond 50 °C, the wavelength shift becomes larger than 0.2 nm per 10 °C.

Fig. 7.10(a) External laser measurement setup including a tunable laser to sweep the wavelength of the
input signal, polarization controller to ensure the input is coupled into the TE mode of the DFB and MRRs, optical powermeter to record the signals from the drop port of the MRRs, and a TEC temperature control to modify, monitor and stabilize the operating temperature of the system. (b) Passive responses of channels 1, 2, 3, and 4 at 20 °C showing matched, low-interfering and adjacent channels. (c) The passive response of channel 1 under different temperatures. A 0.2 nm wavelength shift is observed for a 10 °C temperature change from 20 to 50 °C.

The internal on-chip laser measurement setup is shown in Fig. 7.11. A 1480 nm pump source together with a polarization controller is used to couple the pump signal into the fundamental TE mode of the laser gain waveguide. An external WDM is used to couple out the lasing signal from the pump side of the DFB for analysis. A cleaved SMF-28 fiber is used on each side of the chip to butt-couple the pump onto the chip and output signal from the chip respectively. Optical spectrum analyzers (OSA) I and II are used to monitor the signal from the DFB laser and MRRs, respectively. A thermoelectric cooler (TEC) is used to modify and monitor the operation temperature of the system. In addition, it also stabilize the device temperature by reducing the thermal shift due to the pump power.

Fig. 7.11 Internal laser measurement setup including a 1480 nm laser pump source together with polarization controller to ensure the fundamental TE mode is coupled into the Al2O3:Er3+ DFB laser, optical spectrum analyzers I and II to monitor the DFB laser output and MRR drop port signals, respectively, and a temperature control feedback loop to modify and monitor the temperature of the system.
Figs. 7.12(a) and (b) show the output spectra recorded at different temperatures from OSA I and II, respectively. For the DFB laser, a 0.2 nm wavelength shift is observed for a 10 °C temperature change, which matches to the wavelength shift at the output of the MRR shown in Fig. 7.10(c). Comparing Figs. 7.12(a) and (b), the overall coupling loss from DFB laser to MRR is 2.5 dB. From Fig. 7.12(b), the power at the drop port of the matched MRR reduces as the temperature increases, which is caused by the larger wavelength mismatch between the DFB and MRR at higher temperatures of our temperature control range. The wavelength comparison of the DFB and channel 1 MRR is shown in Fig. 7.12(c). As the temperature increases, the channel 1 MRR has slightly larger wavelength shift compared to the DFB laser. The relative transmission powers from the four channels are recorded in Fig. 7.12(d). More than 15 dB power extinction between channel 1 and the rest of the channels is observed within the temperature range from 20 to 50 °C showing athermal operation, which is sufficient for signal processing in a WDM system [183]. As the temperature is set beyond 50 °C, the power in channel 1 drops by more than 5 dB, due to the wavelength mismatch between the MRR and the DFB, shown in Fig. 7.12(c). Furthermore, Fig. 7.12(d) shows that channel 1 has relatively high power and hence it is the matched channel; channel 2 and 3 have relatively low power therefore they are low-interfering channels; channel 4 has medium power so it is the adjacent channel. This matches with the results from the external laser characterization in Fig. 7.10(b). With the aim of obtaining a more uniform output power over the temperature range from 20 to 50 °C, the DFB laser can be designed to be exactly matched with the resonance of the MRR at 40 °C instead of at 30 °C. Starting at 20 °C, the DFB laser is slightly off the resonance of the MRR. As the temperature increases (to 40 °C, for example), the DFB and MRR resonances will be exactly matched. As the temperature further increases (eg. 50 °C), the DFB resonance will be slightly off with respect to MRR resonance again. This method is equivalent to shifting the red DFB laser resonance up in Fig. 7.12(c), so that red and blue points match exactly at 40 °C. In this way, the transmission power will be more uniform over this operation temperature range.
Fig. 7.12 (a) (b) Optical spectrum of the DFB output (recorded by OSA I) and channel 1 MRR drop port (recorded by OSA II), under different temperatures. (c) Wavelength shift comparison between the DFB laser and channel 1 MRR. (d) Relative power of the different channels over the temperature range of 20 to 50 °C.

In the future, in order to ensure the resonance of the MRR matches with the laser source on a wafer scale, the design of the MRR filter can be improved. For example, high-order filters or contra-directional couplers can be used to get a flat-top response with wider bandwidth [184, 185], and hence relaxing the requirement of perfect alignment. Additionally, an adiabatic ring design [186] can be used to make ring more
fabrication-tolerant. The work presented in this manuscript acts as a prototype for system-level control-free synchronization while further design effort will offer a wafer-scale production solution. Furthermore, these improved MRRs can be cascaded with multiple grating-based lasers [79] for a temperature control-free wavelength multiplexer.

7.2.3 Summary

To sum up, we have demonstrated athermally synchronized operation of an integrated DFB laser cascaded with Si$_3$N$_4$ WDM MRRs on a silicon photonic platform. By making use of the low thermo-optic coefficient of the Al$_2$O$_3$:Er$^{3+}$ laser gain medium and Si$_3$N$_4$, athermal operation is demonstrated over a temperature range from 20 to 50 $^\circ$C. A power extinction ratio of $>$15 dB between matched and unmatched WDM channels is achieved, and a synchronized wavelength shift of 0.02 nm/$^\circ$C is reported. The athermal synchronization approach reported here is not limited to microring filters but can be applied to any Si$_3$N$_4$ filter cascaded with a laser using rare-earth-doped Al$_2$O$_3$ as a gain medium to achieve system-level temperature control free operation.
Chapter 8. Further Applications of Integrated Rare-earth-Doped Lasers

Based on the system level integration for optical communications from the previous chapter, the further applications of rare-earth-doped integrated lasers are covered in this chapter. It also includes two parts: (8.1) cascade of an erbium doped DFB with a silicon based tunable phase array to demonstrate the chip-scale full integration of light source and phase array (8.2) application of erbium doped tunable laser within an optical synthesizer.

8.1 CMOS-compatible optical phased arrays powered by monolithically-integrated erbium lasers

Integrated optical phased arrays, fabricated in advanced silicon photonics platforms, enable manipulation and dynamic-control of free-space light with large aperture sizes and fast steering rates [4, 187, 188]. As such, integrated optical phased arrays have many promising wide-reaching applications, including light detection and ranging (LIDAR) [189], free-space data communications [190], and holographic displays [187, 191]. However, many of these demonstrations have been limited to systems with fiber-coupled off-chip input lasers, which restrict the practicality of the system due to packaging and cost concerns. Recently, phased array systems with on-chip laser sources have been demonstrated using a hybrid III-V/silicon laser integration approach, wherein a III-V epitaxial material is bonded to the silicon chip and patterned to define the gain regions of the on-chip laser [69, 192].

Compared to these hybrid approaches, monolithically-integrated rare-earth-doped lasers [15, 25, 38, 40, 78, 81] offer a higher power, more thermally stable, and narrower linewidth approach to on-chip light generation and require only a single back-end deposition step which could be performed on the wafer scale. Although these lasers have been demonstrated in prior work, thus far a monolithically-integrated rare-earth-doped laser has yet to be demonstrated in an active silicon photonics system where
doped silicon and metal contacts are included for thermal induced refractive index change.

In this section, an erbium-doped laser and an electrically-steerable optical phased array are monolithically integrated in an active silicon photonics platform. An advanced CMOS-compatible 300-mm-wafer silicon photonics platform consisting of two silicon-nitride layers, a silicon layer with eight doping levels, three metal and via layers, a dicing trench, and a gain-film trench is developed. The platform is used to demonstrate an integrated system consisting of an optically-pumped on-chip laser, layer-transition and wavelength-division devices, and an active optical phased array. Lasing with a single-mode output, 30 dB side-mode suppression ratio (SMSR), 0.01% slope efficiency, and 40 mW lasing threshold is shown and one-dimensional beam steering with a $0.85^\circ \times 0.20^\circ$ full-width at half-maximum (FWHM) and $30^\circ / \text{W}$ electrical steering efficiency is demonstrated. This system represents the first demonstration of an active CMOS-compatible silicon photonics system powered by a rare-earth-doped monolithically-integrated laser and paves the way for future monolithic systems, such as data communication links [193] and on-chip optical synthesizers [194].

### 8.1.1 Active silicon photonics platform

The monolithically-integrated system is fabricated at CNSE SUNY in an advanced CMOS-compatible 300-mm-wafer silicon photonics platform consisting of two silicon-nitride layers, a silicon layer with eight doping levels, three metal layers for electrical routing and contact pads, three metal via layers, a dicing trench for fiber coupling, and a trench for deposition of an erbium-doped aluminum oxide ($\text{Al}_2\text{O}_3:\text{Er}^{3+}$) thin film (performed at MIT). Fig. 8.1(a) shows a simplified schematic of the layers in the platform.

In the developed platform, 300-mm-diameter silicon-on-insulator (SOI) wafers with 2 $\mu$m buried silicon-dioxide ($\text{SiO}_2$) thickness and a standard 220-nm-thick silicon (Si) device layer are used. This silicon layer (SE) is patterned using 193 nm deep-ultraviolet immersion lithography with sub-60-nm resolution in two steps: a full etch
to define silicon strip waveguides and a 120 nm partial etch to define 100-nm-thick silicon ridges. Any residual line-edge roughness is reduced using oxidation and removal steps. The active silicon devices, such as thermal phase shifters [195] and modulators [196], are then N- or P-type doped to define junctions for modulation or increase electrical conductivity for heating. A suite of eight dopant masks are used with varying dopant species (Arsenic, Phosphorus, and BF2), doses, and energies to enable P- and N-type doping for both full-height and partial-height waveguides.

Next, a 135-nm-thick tetraethylorthosilicate (TEOS) plasma-enhanced-chemical-vapor-deposition (PECVD) SiO2 layer is deposited on top of the silicon layer and its top surface is planarized using a chemical-mechanical polishing step. A 200-nm-thick silicon-nitride layer is then deposited using another PECVD process, polished using a top surface polishing process to reduce optical scattering loss, annealed to reduce absorption, patterned using 193 nm immersion lithography, and processed using a wet oxidation step to reduce side-wall roughness. This process is then repeated with a second 100-nm-thick SiO2 layer and a second 200-nm-thick SiN layer. The two resulting SiN layers, called the first nitride (FN) and second nitride (SN), define the passive SiN devices in the system and the etch stop for the gain trench respectively.

At the top of these three waveguide layers, three metal and via layers are formed using a series of additional SiN etch stop layers, trenches, metal depositions, and SiO2 layers. A tungsten via (CB) is used for electrical contact to the silicon layer, two 1-µm-thick copper metal layers (M1 and M2) are patterned to enable routing of electronic signals, two vias (V1 and V2) are used for interconnection between metal layers, and an aluminum metal layer (ML) is used to define pads for electronic probe connection.

Next, a 4-µm-deep trench (TS) for deposition of the gain media is etched into the SiO2 using the SN layer as an etch stop. An additional 100-nm-thick SiO2 layer is then deposited as a liner within the laser trench, such that the final spacing between the FN layer and the bottom of the trench is 200 nm. Finally, a deep dicing trench is etched to define the edge of each chip and enable dicing and fiber edge coupling, and the oxide
above each ML pad is removed to create the opening of pads.

After dicing the wafer into individual reticles, a 1170-nm-thick Al₂O₃:Er³⁺ film is deposited on top of the chip via reactive co-sputtering at MIT as a back-end-of-line process [15]. A measured 397 °C deposition temperature and 10 W doping energy setting on RF gun of the deposition machine are chosen to ensure that the metal vias in the system do not degrade through the deposition process [25] and that the laser performance is not sacrificed [40].
Fig. 8.1(a) Simplified layer schematic of the monolithically-integrated silicon photonics platform utilized for the phased array system (not to scale). (b) Simplified schematic of the phased array system with an on-chip laser showing major components and process layers (not to scale). (c) Photograph of the experimental setup.

8.1.2 System architecture and characterization

The integrated phased array system consists of an optically-pumped on-chip laser, layer-transition, wavelength-division devices, and an electrically-steerable integrated optical phased array. Fig. 8.1(b) shows a simplified schematic of the system.

The system uses an on-chip distributed-feedback (DFB) laser (similar to [38]) as the optical source. The gain waveguide of the DFB laser consists of five silicon-nitride segments patterned in the FN layer underneath a 30-µm-wide TS trench and Al₂O₃:Er³⁺ thin film. The widths of and gaps between the silicon-nitride pieces are both selected to be 300 nm to ensure high transverse-electric mode overlap and confinement within the gain film for both the 980-nm pump wavelength and 1599-nm signal wavelength (the confinement factors in the film are calculated to be 96.9% and 89.8% for the pump and signal modes, respectively, using a two-dimensional mode solver). The DFB cavity is formed by patterning a 230-nm-wide silicon-nitride grating in the FN layer along both sides of the gain waveguide. To enable a strong single-mode lasing output at the desired signal wavelength, each grating is designed with a 509 nm period, 0.5 duty cycle, 350 nm lateral gap between the gain waveguide and the grating. A quarter-wave gap is located at the center of the cavity. The total length of the DFB laser is 2 cm, limited by the size of the reticle.

At the far end of the DFB, a three-stage 600-µm-long layer transition is designed to adiabatically couple the mode from the five-segment gain waveguide under the trench into a 1.2-µm-wide double-layer (FN-and-SN) silicon-nitride waveguide. After the layer transition, the 1599 nm signal wavelength is then separated from the 980 nm pump using a wavelength-dependent directional coupler acting as a wavelength-division multiplexer (WDM). On the signal output port of the WDM, another
200-µm-long layer transition adiabatically couples the signal into a 400-nm-wide silicon (SE) waveguide connected to the input bus of the integrated phased array.

The integrated optical phased array utilizes a grouped cascaded phase shifter architecture, which controls the relative phase applied to an array of antennas (architecture similar to [189]). Evanescent couplers with 120 nm coupling gaps and increasing coupling lengths are used to uniformly distribute the input power from the bus waveguide to 49 grating-based antennas with a 2 µm pitch. The antennas utilize a full-etch perturbation geometry (a 64 nm perturbation is etched with a period of 621 nm along the length of the 500-µm-long and 610-nm-wide antennas) to enable radiation out of the plane of the chip at the signal wavelength. A phase shifter is placed on the bus between each evanescent coupler to enable cascaded electronic phase control to the antennas for one-dimensional beam steering. A doped waveguide-embedded thermal phase shifter in an adiabatic-bend configuration is used to ensure thermally-efficient control with low optical loss [195]. The phase shifters are grouped and controlled by 6 electronic signals to reduce control complexity while enabling fine tuning for any fabrication-induced phase variations [189]. Given the 0.5 mm×0.1 mm aperture size and 2 µm antenna pitch, a 0.80°×0.16° main beam FWHM and grating lobes at ±51° are expected in the far field of the array when the main beam is centered at 0°.
Fig. 8.2(a) Diagram illustrating the experimental setup used to characterize the on-chip laser. Measured optical spectrum of the laser showing (b) the full spectrum including the amplified spontaneous emission and (c) the lasing peak at 1599 nm.

To characterize the fabricated system, an off-chip 980-nm-wavelength laser diode is used for optical pumping, as shown in Fig. 8.2(a). The pump is routed through a fiber WDM to enable single-sided characterization of the on-chip laser’s signal using either an optical spectrum analyzer (OSA) or a power meter. A polarization controller is used to ensure that the fundamental transverse-electric mode is coupled into the gain waveguide. The pump is then coupled into the on-chip laser with 254 mW of optical power launched from the input fiber facet, as shown in Fig. 8.1(c). Fig. 8.2(b)-(c) show the normalized laser spectrum, as measured using an OSA. A single lasing peak at 1599 nm is observed.
nm with a 30 dB SMSR is observed. Additionally, by varying the input pump power and measuring the resulting signal power using a power meter, the slope efficiency and launch power lasing threshold of the on-chip laser are estimated to be 0.01% and 40 mW, respectively.

Next, a free-space optical setup is utilized to image the far field of the phased array onto an IR camera. The imaging setup consists of an objective with either a 50° or 16° field of view to serve as a near-to-far-field converter, a singlet lens for magnification, and an InGaAs short-wave-infrared camera [188]. Fig. 8.3(a) shows the measured far-field intensity of the array. Cross-sectional views of the intensity in the array dimension, $Y$, and the antenna dimension, $q$, are shown in Fig. 8.3(b). As expected, the system forms a collimated beam in the far field of the array with a measured main-beam FWHM of $0.85\times0.20^\circ$, which closely matches both the theoretical value of $0.80\times0.16^\circ$ and the value previously reported using a similar phased-array architecture ($0.85\times0.18^\circ$) [189].

Finally, a multi-pin electrical probe is used to vary the electrical power applied across the integrated phase shifters in the array and steer the generated beam in the far field. With 0.5 W of applied electrical power, $15^\circ$ of steering in the array dimension, $Y$, is observed, as shown in Fig. 8.3(c). This closely matches the thermal steering efficiency observed previously using a similar architecture [189], confirming that the film deposition procedure does not detrimentally affect the via integrity.

For future improvements to this system, a laser source with a tunable wavelength output (similar to [197]) could be implemented to enable steering of the far-field spot in the antenna dimension (since the antennas in the phased array are based on grating principles, as the wavelength of the input light is tuned, the effective period of the antennas and, subsequently, the angle of the radiated light varies). Furthermore, the relatively low slope efficiency of the current on-chip laser compared to previous reports [39, 40] is largely contributed by the loss of the narrow 30-µm-wide gain trench. To improve the overall system performance, laser devices with wider gain trenches could be designed to improve the laser efficiency.
8.1.3 Summary

In summary, an advanced CMOS-compatible 300-mm-wafer silicon photonics platform with monolithically-integrated laser sources has been developed. The platform has been used to demonstrate an electrically-steerable integrated optical phased array with a grouped cascaded phase shifter architecture powered by an on-chip erbium-doped DFB laser. Lasing with a single-mode 1599-nm-wavelength output, 30 dB SMSR, 0.01% slope efficiency, and 40 mW lasing threshold has been shown. Beam forming and one-
_dimensional beam steering with a 0.85°×0.20° FWHM and 30° /W electrical steering efficiency have been demonstrated. This system enables integrated CMOS-compatible beam steering capabilities for a variety of applications, ranging from LIDAR to free-space data communications [187, 189].

Furthermore, this work represents the first demonstration of a monolithic rare-earth-doped laser source integrated into an active CMOS-compatible silicon photonics system. The successful realization of such a platform paves the way for future advanced monolithic silicon photonics demonstrations, ranging from integrated communication links [193] to on-chip optical synthesizers [194].

8.2 Silicon-photonics-based optical frequency synthesizer

Optical frequency combs that phase coherently build a link from optical frequency down to measurable radio frequency has been proven extremely useful for applications including frequency metrology and optical atomic clocks [198]. Such a system will inherently have a positive impact on precision frequency synthesis, where any CW laser oscillator can be coherently stabilized and tuned over the wide bandwidth of a phase-locked frequency comb, thus synthesizing precise optical frequencies on demand [199]. For such a system to be widely available at low cost, they should be manufacturable in the CMOS foundry. In this section, we demonstrate our progress towards such a system using silicon on insulator platform. We show an octave spanning coherent and phase locked (to a microwave reference) comb generation by detecting and stabilizing the pulse repetition rate \(f_{\text{rep}}\) and carrier offset frequency \(f_{\text{co}}\) of a mode-locked laser (MLL), which is used for supercontinuum (SC) generation and f-2f conversion with the help of second harmonic generation (SHG) in a silicon waveguide. Subsequently, a low noise integrated CW laser is phase locked in the C-band to the stabilized frequency comb for optical frequency synthesis.

8.2.1 Synthesizer system architecture and operation

A MLL is used to pump the SC waveguide at 1.9 µm with the repetition rate of 200 MHz,
18 pJ of coupled energy and pulse width over 50 fs, as shown in Fig. 8.4. The SC is generated by designing the waveguide for optimum group velocity and third order dispersion, resulting in strong signal generation at f (~2.3μm), 2f (~1.15μm), and in C-band (~1530-1565nm), as shown in Fig.2. See [9] for detail.

Fig. 8. 4 The silicon photonic synthesizer circuit with its photonics and electronics arms. The MLL is being stabilized with the help of SC and SHG waveguide (see text for detail). The color and black arrows represent optical and electronic signals respectively. The vias of the SHG waveguide are to apply reverse bias voltage using metal contact to the P and N doped part of the device. The pump to the CW laser is a 980 nm diode laser. The solid line from the 10MHz reference is to synchronize the respective circuit. The dash line from fceo lock circuit (ckt) and cw-to-comb lock circuit to the frequency counter is denoting measurement. The synthesized signal is shown in dashed arrow from the CW laser.

The optical synthesizer contains three locking loops, frep, fceo and CW-to-comb locking. For frep locking, the fifth harmonic of the MLL is directly detected by a photodetector (PD) and then compared with a RF synthesizer (frep RF syn) to generate the phase error signal, which is fed back to MLL PZT. To detect fceo, f-to-2f interferometry is required. The f part of the SC signal is sent through a dichroic mirror into the SHG waveguide where it is quasi-phase matched to the 2f signal being
produced by periodically applying DC field orthogonal to the propagation direction of
the optical field in the waveguide. The SHG conversion efficiency is 13%/W under
21V DC application [8]. The upconverted 2f signal and the 2f part of the SC signal are
combined in a 50:50 coupler and beating in a balanced photodetector (BPD), which can
maximize $f_{\text{ceo}}$ and suppress $f_{\text{rep}}$ (by $>20\text{dB}$) simultaneously. A tunable delay line (TDL)
is used in one of the 2f arms to ensure maximum temporal overlap of the two 2f pulses
so as to maximize the SNR of the $f_{\text{ceo}}$. The measured $f_{\text{ceo}}$ signal is shown in the inset of
Fig. 8.4(b) which is stabilized by feeding back to the MLL pump current using a similar
control circuit as in $f_{\text{rep}}$ locking loop. Finally, in the cw-to-comb locking, the output of
a low noise, sub-MHz linewidth, C-band laser, whose gain material was fabricated by
depositing erbium-doped aluminum oxide ($\text{Al}_2\text{O}_3$:Er$^+$) at the top of a lowloss silicon
nitride platform (same tunable laser in Chapter 4), is beating with the C-band signal
(1560nm) of the SC using another 50:50 coupler and BPD, and the generated phase
error signal from control electronics is fed to the integrated heater of the CW laser with
$\sim10\ \mu\text{s}$ response time. The RF syns in all three locking loops are locked to the same 10
MHz oscillator, which can guarantee that the final optical synthesizer output is also
locked to this RF reference.
Fig. 8.5(a) The SC spectrum with the f, 2f and C-band part shown in yellow band. (b) The measured $f_{\text{ceo}}$ signal (inset) and its frequency instability. (c) Frequency deviation of the stabilized CW laser relative to the optical comb frequency to which it is locked. (d) The frequency instability of the CW-to-comb beat note.

The whole synthesizer was successfully operated over 20 minutes, as shown in Fig. 8.5(c). The frequency instability (Allan deviation) for the $f_{\text{ceo}}$ and CW-to-comb beat note relative to the 10 MHz reference are shown in Fig. 8.5(b) and (d), both of which are $<1 \times 10^{-14} @ 1s$ and $< 1 \times 10^{-15} @ 100s$. The instability performance of $f_{\text{rep}}$ is much better due to the high SNR in PD detection. Therefore, a frequency instability of $<1 \times 10^{-15} @100s$ can be guaranteed for this synthesizer.

### 8.2.2 Summary

To sum up, we have demonstrated first silicon photonics based frequency synthesizer with a relative frequency instability $< 1 \times 10^{-15}$ at 100 s. Future work will include integrated MLL and exclude coupling loss compensating amplifiers (Tm:ZBLAN for f amplification and EDFA for CW laser). Our work leads to various applications including optical communication, spectroscopy, metrology, and integrated atomic clocks.
Chapter 9. Self-pulsing Investigation on Rare-earth-Doped Lasers

Self-pulsing behavior has been observed in our rare-earth-doped integrated laser. One example is what we have mentioned in fully integrated erbium-doped tunable laser section: time domain stability issue. In order to investigate the possible causes of this stability issue, in this section, a fiber laser is set up to study the self-pulsing behavior.

In solid state lasers, the self-pulsing behavior has been investigated theoretically and experimentally [86, 87]. The cause of such behavior is ion-pair formation in gain medium, under the condition that ion pair concentration is more than 5% [87]. The self-pulsing (or Q-switching) behavior comes from the energy transfer between two close ions, as shown in erbium energy diagram below (Fig. 9.1). The energy transfer lifetime is on the order of μs, compared to ms level active ion lifetime. After the 2\textsuperscript{nd} ion takes the energy from 1\textsuperscript{st} ion, the electron will quickly jump up to 4I_{9/2} level and decay back to 4I_{9/2} level without emission. Such energy transfer process causes Q-switching of the laser. The rate equation is solved under two conditions: without and with quenched ion. The time domain stability is shown in Fig. 9.2(a) and (b) below. Fig. 9.2(a) shows the relaxation oscillation process after population inversion is reached. The laser signal becomes stable in 0.01 s after the relaxation oscillation process decayed. In comparison, Fig. 9.2(b) shows the time domain signal by adding additional quenched ion lifetime in rate equation. After population inversion is reached, self-pulsing is observed. The pulse interval is about 100 μs, which corresponds to the life time of the energy transfer between two closed ions mentioned above.
Fig. 9.1 The energy level of two close erbium ion, showing the self-pulsing mechanism: energy transfer between two close ions.

Fig. 9.2(a) laser time domain simulation result by solving the rate equation without quenched ion: the laser becomes stable after the 0.01s relaxation oscillation process; (b) laser time domain simulation result by solving the rate equation with quenched ion: the laser has self-pulsing with pulse interval of 100 µs which corresponds to the lifetime of the energy transfer.

Besides ion quenching mentioned above, by introducing incoherent feedback outside the laser resonance cavity [200, 201], the pulses can also be generated. Fig. 9.3 below shows an example of how feedback affects the laser time domain stability: The laser diode on the left lases in TE mode. Outside the cavity there is a Faraday rotator,
polarizer and mirror. The polarization of TE output will be rotated to TM after the external cavity feedback loop. The TM signal injected back into the laser may cause it to lase in TM mode and affect the time domain stability of the laser.

![Diagram](image)

**Fig. 9.3** An example condition showing how optical feedback affect the laser time domain stability.

Erbium doped laser, either in fiber or on-chip, are extremely useful due to its emission wavelength. The on-chip erbium doped laser is promising for light source in silicon photonics, as has been shown high power [115] and wafer scale [41]. While the pulsing has also been observed in these on-chip lasers, which might have detrimental effect for applications. In this section we want to study the cause of such un-stability by looking into ion pair and optical feedback due to scattered light. A fiber laser system is setup as analogy to integrated laser system.
9.1 Ion quenching investigation

First, ion-pair formation (or ion quenching), which is one of the potential causes of the self-pulsing, is investigated. The experimental setup is illustrated in Fig. 9.4. The purpose of two isolators is to eliminate the optical feedback in laser system. The reflectivity of two DBRs is 99% and 76% on left and right respectively. The WDM on the right side split the lasing signal and residue pump. In order to confirm the cause of self-pulsing, three EDFs are used: (1) Er-16, with $6.8 \times 10^{18}$ ions/cm$^3$ doping concentration, 3% ion-pair concentration, and 0.16 dB/cm absorption at 1530 nm; (2) Er-80, with $3.7 \times 10^{19}$ ions/cm$^3$ doping concentration, 14% ion-pair concentration, and 0.80 dB/cm absorption at 1530 nm; (3) Er-110, with $6.6 \times 10^{19}$ ions/cm$^3$ doping concentration, 16% ion-pair concentration, and 1.10 dB/cm absorption at 1530 nm. It is worth to mention that the integrated CW laser reported in [115] has a doping concentration of $9.0 \times 10^{19}$ ions/cm$^3$.

![Schematic diagram of erbium doped fiber laser](image)

Fig. 9.4 Schematic diagram of erbium doped fiber laser. WDM: Wavelength Division Multiplexing; DBR: Distribute Bragg Reflector; EDF: Erbium Doped Fiber

The time domain of 1550 nm signal has been measured for three doping levels, as shown in Fig. 9.5(a)-(c). (a) is the case for low doping: as pump increases near the lasing threshold, the laser keeps working in CW; while (b) and (c) show the cases for high doping (>5% ion-pair concentration): the laser operates in self-pulsing regime near the lasing threshold. Both (b) and (c) shows that as pump goes further from threshold, the repetition rate increases and eventually the CW regime dominates the self-pulsing. In addition, the observation proves that the self-pulsing effect in this fiber laser, with proper optical isolation, is caused by ion pair in high doping concentration instead of
feedback.

Fig. 9.5 Stability measurement near the lasing threshold under different doping concentrations (a) Er-16 (b) Er-80 (c) Er-110. As the doping concentration becomes higher, the laser becomes more unstable (d) Er-110 under resonant pumping, the laser becomes stable.

9.2 Optical feedback investigation

With the aim of investigating how optical feedback will affect the pulsing, the setup in Fig. 9.4 has been modified to the setup shown in Fig. 9.6. Er-80 is used in laser cavity. The reflectivity of the additional DBR is 93%. A tunable attenuator, ranging from 0 dB to 60 dB, is used together with DBR to provide variable feedback. Fig. 9.7 shows the pulsing trend under different attenuation value: (a) is the case under the condition of
high feedback, the pulse peak value becomes higher, which means that the feedback has constructive interaction with self-pulsing. When the attenuation is increased to 20 dB, the feedback is decreased, and the peak value of the pulse decreases. In this case, the feedback has destructive interaction with self-pulsing. When the attenuation is further increased to 40 dB and even 60 dB, the measurement result tends to be the same as Fig. 9.5(b), which means the feedback has been shut off by such amount of attenuation. In order to further verify that the cause of pulsing is due to ion pair formation rather than optical feedback, the EDF in Fig. 9.6 has been replaced with lowly doped Er-16. Stable curves are observed near the lasing threshold under various feedback conditions. Fig. 9.7(c) shows the case under 0dB attenuation.

Fig. 9.6 Erbium doped fiber laser setup with feedback.
9.3 Self-pulsing suppression

Several ways have been reported to stabilize the laser against self-pulsing [88, 202, 203]. Among them, an effective one is resonant pumping [202]. The idea is that when pump wavelength is close to signal, the pump will also serve as gain limiter, which damps out the oscillations in population inversion. Hence the pulsing can be suppressed. The mechanism is shown in Fig. 9.8 below. This method is also implemented in our setup, with 980 nm pump replaced by 1490 nm one. The two WDMs in Fig. 9.4 also need to be replaced by the ones work with 1490 nm. The time domain measurement for
Er-110 fiber is illustrated in Fig. 9.5(d). Comparing the Fig. 9.5(c) and (d), the self-pulsing has been significantly suppressed, while the output power becomes relatively lower.

Fig. 9.8 Energy level diagram of two close erbium ions. As pump wavelength is close to signal, the pump photon will stimulate the emission of electrons from upper level, which damps out the oscillations in population inversion.

**9.4 Summary**

To sum up, we report the self-pulsing in DBR based erbium doped fiber laser under different doping level, and verified that the pulsing is mainly caused by ion pair in highly doped gain instead of feedback. A controlled feedback is created by an additional DBR and it is varied quantitatively by a tunable attenuator. Such feedback is found to either constructive or destructive interact with laser beam. By using 1490 nm pump instead of 980 nm, the self-pulsing is suppressed significantly.
Chapter 10. Conclusion and Recommendation for Future Work

10.1 Conclusion

In conclusion, we demonstrate various integrated lasers based on rare-earth-doped Al₂O₃ glass, including erbium, thulium, and holmium doped lasers. The effectiveness of the wafer-scale single-step Al₂O₃ thin film deposition process is proven, which can be used as an alternative approach for laser integration. The advantages of these lasers, including wide gain bandwidth, narrow linewidth, thermal stability and lasing wavelength control, are presented.

In the erbium doped laser section, a novel narrow linewidth laser design called distributed phase shift DFB is demonstrated, showing a linewidth of 5 kHz. Next, in order to overcome the Al₂O₃ thin film non-uniformity issue from deposition machine, a reliable curved cavity design is proposed, showing > 6 times lower lasing threshold and >2 times maximum lasing power compared to straight cavity design. Furthermore, an erbium doped fiber laser with a tunable interio-ridge Si microring cavity is presented, achieving continuous wavelength tuning over the C-band and wavelength-swept rate of 91300 nm/s. Additionally, the first monolithically integrated erbium-doped tunable laser on a CMOS-compatible silicon photonics platform is demonstrated, with a tuning range from 1527 nm to 1573 nm, and a SMSR of >40 dB.

In the thulium doped laser section, firstly, a microring cavity based laser is presented. This ultra-compact laser design have a threshold as low as 773 (226) µW and a slope efficiencies of up to 24% (48%) vs. on-chip (absorbed) pump power. Secondly, high-power thulium DFB and DBR lasers integrated on a silicon chip are shown. By varying the grating period, single-mode lasers with wavelengths from 1800 nm to 1950 nm are demonstrated within the thulium gain bandwidth. The maximum output power of 387 mW and SMSR of > 70 dB are achieved. In order to further extend the lasing wavelength beyond 2 µm, holmium doped DFB lasers integrated on a silicon
chip are demonstrated for the first time. A laser output power of 15 mW is reported at a wavelength of 2050 nm with a slope efficiency of 2% and greater than 50 dB SMSR. The lasing wavelength control is shown by changing the Al₂O₃: Ho³⁺ film thickness.

For further applications of the lasers demonstrated above, two system level integrations are demonstrated for optical communication. The first demonstration is the integration of a WDM light source in a silicon photonics platform by cascade of Al₂O₃: Er³⁺ DFB lasers. Simultaneous operation of four DFB lasers has been achieved with a total power of −10.9 dBm, corresponding to an average power of −16.9 dBm and a 38.1 ± 2.5 dB SMSR for each DFB laser. The second demonstration is an athermally synchronized operation of an integrated laser cascaded with WDM filters. By making use of the low thermo-optic coefficient of the Al₂O₃:Er³⁺ laser gain medium and Si₃N₄, athermal operation is demonstrated over a temperature range from 20 to 50 °C. Furthermore, beam steering of integrated optical phased array powered by an erbium doped DFB laser on the same chip is presented. Beam forming and one-dimensional beam steering with a 0.85° × 0.20° FWHM is achieved. In addition, the first silicon photonics based frequency synthesizer with a relative frequency instability < 1×10⁻¹⁵ at 100 s is demonstrated. The optical frequency synthesizer utilizes a monolithically integrated erbium doped tunable laser locked to a silicon-photonic-based octave spanning optical frequency comb. This work can lead to various applications including optical communication, spectroscopy, metrology, and integrated atomic clocks. All these results above demonstrate integrated rare-earth-doped lasers to be of interest as efficient monolithic light sources for emerging silicon-based photonic microsystems.

### 10.2 Recommendations for future work

The future work can be categorized into the following three aspects:

First, the Q value of the laser cavity is limited by gain film thickness non-uniformity along the straight laser cavity. One solution is to design a curved shape cavity which follows the circular symmetry of the Al₂O₃ thin film deposition system, as discussed in Chapter 2. An alternative solution is to use a DBR cavity structure, and
design the grating in bottom nitride (BN) layer, so that the mode in gain waveguide does not have any overlap with the grating. In this way, the mode in the grating reflector will not have interaction with gain film and hence the effect of thickness non-uniformity on cavity Q can be minimized. An updated design is shown in Fig. 10.1 below.

![Cross sectional view of the silicon photonic platform showing different layers. TS-Trench (for gain film); FN-first nitride layer; SN-second nitride layer; BN-bottom nitride layer; DN-double nitride layer (first nitride + second nitride); (b) updated Ho laser design with grating reflector in BN layer.](image)

Fig. 10.1(a) Cross sectional view of the silicon photonic platform showing different layers. TS-Trench (for gain film); FN-first nitride layer; SN-second nitride layer; BN-bottom nitride layer; DN-double nitride layer (first nitride + second nitride); (b) updated Ho laser design with grating reflector in BN layer.

Second, rare-earth-doped laser can be pumped by pump diode, therefore pump diode can be integrated on-chip to have a fully integrated laser. In this way, the 6-7 dB fiber-to-chip coupling loss for pump can possibly be reduced and the device can achieve better stability and compactness.

Third, to achieve electrically pumped rare-earth-doped laser, we think finding the proper host material is the key. Scientists have been trying to make electrically pumped erbium doped silicon slot waveguide for amplification, while lasing has not been achieved due to the high loss of the waveguide (ref. [204]). When the host material becomes electrically conductive for carriers to flow, it also becomes optically lossy at
the same time. A well balanced point needs to be found between low propagation loss and high electrical conductivity in order to demonstrate electrically pumped rare-earth-doped waveguide laser.
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Appendix I Standard Operation Procedure for an Al₂O₃ Deposition Run on AJA Sputter (ATC Orion)

(a) Chips preparation
1. Prepare a witness sample (6 μm thick SiO₂ on Si) for film thickness and loss characterization;
2. Place the chips and the witness sample into Acetone container, and use ultrasonic bath to clean them for 4-6 mins;
3. Place the chips and the witness sample into IPA container, and use ultrasonic bath to clean them for another 4-6 mins;
4. Use N₂ gun to dry the chips, and check the chips under microscope;
5. If there are dirty particles within the trench or at the top of laser waveguide, use Q-tip to sweep lightly, then rinse the chip with IPA, and dry the chip with N₂ gun;
6. After cleaning, place the chips and witness sample on the substrate holder, as shown in Fig. I. 1 below.

Fig. I.1 Chips and witness sample placed on the substrate holder

(b) Load the samples into the chamber
7. Load the Al and Er (or Tm, Ho) targets on gun 2 and 3 respectively, make sure there is a copper buffer between the gun and the target;
8. Open and close the shutters of gun 2 and 3 to test; (to make sure clean deposition
condition, the shutter of Al gun should be replaced for every deposition run, otherwise, there will be Al flakes on the shutter after high temperature deposition. The shutter can be cleaned by bead blasting);

9. Use vacuum machine to clean the dust/particles inside the chamber and the shutters of the guns;

10. Load the samples in, lower down the substrate stage to “QCM” mark, as shown in Fig. 1.2(a) below;

11. Move the QCM (crystal monitor) at the top of substrate holder, make sure the shade covers the substrate holder well when the substrate holder is under rotation;

12. Press the “Xtal life” on the crystal monitor panel to check the lifetime of the crystal monitor; The location of the button is highlighted in red in Fig. 1.2(b) below.

13. Setup the crystal monitor for Al₂O₃ material (setting: density 3.97, Z-factor 0.34);

14. Close the chamber and starts pumping down. (It normally takes 2 hours to reach <2e-5 Torr pressure range).

(a)  

(b)  

Fig. 1.2(a) Substrate stage height controller at the bottom of the deposition chamber (b) Control panel of crystal monitor

(c) Pre-sputter (for deposition rate calibration)

15. Once the chamber based pressure is <2e-5 Torr, open the “GAS 1” (Ar) and “GAS 3” (O₂) on the touch screen monitor (Fig. 1.3(a) below), turn on Ar gas
control to 11.0 sccm flow rate;

16. Open the CM at the back of chamber (Fig. I.3(b) below), set the chamber pressure to be 30 mTorr for plasma ignition;

17. Switch on the power of gun 2 and 3 (with 60 W initialized setting power), record down the bias voltage for both guns; (If the plasma does not ignite, open and close the shutter of the gun quickly for ignition)

18. Increase gun 2 power to 200 W slowly, and then increase gun 3 power to 100 W slowly, record down the bias voltage;

19. Set the pressure to 3 mTorr for pre-sputter process;

20. Decrease gun 3 power to set for doping (normally 10 W for erbium, 16 W for thulium, 18 W for holmium);

21. Turn on the O₂ gas control and turn up to 0.5 – 1.0 sccm flow rate;

22. Open the shutters for both guns, increase the O₂ flow, until the reading of crystal monitor becomes 6.5 A/s, then record down the voltage bias range (+3 nm) of the Al target; (during the real deposition under high temperature, this voltage bias range should correspond to the 5.5 nm/min. For more detail, please refer to the section 2.3 of this thesis)

23. Close the shutters for gun 2 and 3, set chamber pressure from 3 mTorr to 30 mTorr, turn O₂ flow rate to 0 sccm;

24. Remove the QCM from the back side of the chamber, raise the stage up to “run” from the bottom side of the chamber;

25. Ramp up temperature using heater control panel (Fig. I.3(c) below). The ramp up rate can be set to 90 °C/min. After the reading temperature on display reaches the deposition temperature (eg. 550 °C), wait for 15 mins until the thermal equilibrium is reached.
(d) **Sputter**

26. Set the chamber pressure from 30 mTorr to 3 mTorr, increase the O\textsubscript{2} flow rate slightly to 0.3-0.5 sccm;

27. Open the shutters 2 and 3, increase the O\textsubscript{2} flow rate slowly until the gun 2 bias voltage starts to drop fast and significantly, record down the bias voltage right before dropping (the “knee” point of O\textsubscript{2} flow – bias voltage curve);

28. As the deposition goes on, adjust the O\textsubscript{2} flow rate to keep the bias voltage at the “knee” point; (typically the O\textsubscript{2} flow rate range increase from 0.8 to 1.6 sccm during a deposition process)

29. Calculate the estimated deposition ending time for target thickness.

(e) **Cooling down and unload the samples**

30. At the end of deposition, close the shutters 2 and 3;

31. Decrease the power on gun 2 and 3 to 0 W, close both guns;

32. Decrease O\textsubscript{2} flow rate to 0, close “GAS 3”;

33. Set the chamber pressure to 30 mTorr;

34. Ramp down the temperature, with ramp rate of 10 °C/min;

35. After around 1.5 hours cooling down process, the chamber can be open, the samples and targets can be unloaded.
Appendix II Matlab Code for Laser Simulation

The simulation codes for grating are listed below. There are three parts: (a) 2D mode solver; (b) pump/signal mode overlap calculation; (c) Amplification calculation based on rate equation; and (d) Lasing power calculation (DBR cavity). Code (a) is modified based on the original code written by previous student Milos Popovic. The laser gain waveguide structure is defined in code (b) which calls code (a). It calculates out both pump and signal modes for laser, and saves the mode profile. These mode profiles are called in code (c), which solves the rate equation and calculates out the amplification of the gain medium. Lastly, the amplification obtained from code (c) is used in code (d) to calculate out the lasing power under different pumping scheme by adding reflection mirrors to form DBR cavity.

(a) 2D Mode solver

% Step-index 2D-cross-section waveguide modesolver function

% Syntax: [N,F,V] = sisolver3d(nlyrs, dlyrsx, dlyrsy, dxy, k0, OPTS)
% % Inputs: nlyrs       [NxM] matrix of section indices along y (1:N) and x (1:M)
% %          dlyrsx     [1xM] vector of M section widths along x
% %          dlyrsy     [1xN] vector of N section heights along y
% %          dxy        [1x2] [dx dy] discretizations along x and y
% %          k0         Free space k-vector (wavelength)
% %          OPTS       Any options to be passed to m2wcyl
% %
% %  OPTS.epsavg     [OPTIONAL] chooses 'pn' (default) or 'simple' dielec averaging (pn = parallel/normal field)
% %  OPTS.radius     [OPTIONAL] set radius of left interface if bend
% %
% %  OPTS.NMODES_CALC, OPTS.NMODES_KEEP, OPTS.mu_guess... and any other m2wcyl accepted options can also be passed in.
% %  OPTS.PARALLEL   [OPTIONAL] if set to 1, use Star-F.
function \([N,F,V] = sisolver3d(nlyrs, dlyrsx, dlyrsy, dxy, k0, OPTS)\)

% Parse the input structure
% \([MM,NN] = size(nlyrs);\)

% Step-index regions
dlyrs = dlyrsx();'; dlyrsy = dlyrsy();';
MM = length(dlyrs); NN = length(dlyrsy);
dx = dxy(1); dy = dxy(2);

% Parse the input structure
% \([MM,NN] = size(nlyrs);\)

% Step-index regions
dlyrs = dlyrsx();'; dlyrsy = dlyrsy();';
MM = length(dlyrs); NN = length(dlyrsy);
dx = dxy(1); dy = dxy(2);

dlyrsx(end) = round(sum(dlyrsx)/dx)*dx + 0*1e-3*dx - sum(dlyrsx(1:end-1));
dlyrsy(end) = round(sum(dlyrsy)/dy)*dy + 0*1e-3*dy - sum(dlyrsy(1:end-1));
xint = [0 cumsum(dlyrsx)]; yint = [0 cumsum(dlyrsy)]; % Interface coordinates
if (VMODE > 0)
    fprintf('Domain limits: (x,y) = user passed (0..%f, 0..%f),
    rounding last layer to pixel grid (0..%f, 0..%f) | Pixel grid size = %d x %d
    ', sum(dlyrsx), sum(dlyrsy), xint(end), yint(end),
    round([xint(end)/dx yint(end)/dy]));
    fprintf( '   x-interface positions at: ');
    for k = 1:length(xint), fprintf(' %f ', xint(k)); end
    fprintf('
');
    fprintf( '   y-interface positions at: ');
    for k = 1:length(yint), fprintf(' %f ', yint(k)); end
end
x = [0 : dx/2 : xint(end)]; y = [0 : dy/2 : yint(end)]; % Grid coordinates
xint(1) = -inf; xint(end) = +inf; yint(1) = -inf; yint(end) = +inf; % [MP] Put edge interfaces to infinity to avoid index averaging at domain edges

if ((nargin > 5) & isfield(OPTS,'epsavg'))
    if strcmp(OPTS.epsavg,'simple')
        flagepsavg = 0;
    else
        flagepsavg = 1; % Use parallel/normal field determined epsilon averaging for smooth distribution
    end
else
    flagepsavg = 1;
end

if(flagepsavg == 0) % Standard (area-arithmetic) index averaging for pixels, then those are averaged for pixel edge tensor components for Ex, Ey, Ez
    if(VMODE>0) fprintf('Using simple arithmetic dielectric averaging.\n'); end
    % Generate index distribution with area-weighted dielectric averaging (justified by Ampere's law) at interfaces
    xp = x(2:2:end-1); yp = y(2:2:end-1); npsq = zeros(length(xp), length(yp));
    for mm = 1:MM
        % along x-coordinate
ixin = find((xp+dx/2) > xint(mm) & (xp-dx/2) <= 
xint(mm+1)); % Find all pixels with at least some 
part inside region (mm,nn) 
xpmin = max(xint(mm), xp(ixin)-dx/2); xpmax = min(xint(mm+1), 
xp(ixin)+dx/2); % Min and max coords of pixel *in* region (mm,nn) 
for nn = 1:NN % along y-coordinate 
iyin = find((yp+dy/2) > yint(nn) & (yp-dy/2) <= yint(nn+1)); 
ypmin = max(yint(nn), yp(iyin)-dy/2); ypmax = min(yint(nn+1), 
yp(iyin)+dy/2); % Min and max coords of pixel *in* region (mm,nn) 

npsq(ixin,iyin) = npsq(ixin,iyin) + (xpmax-
xpmin)'*(ypmax-
ypmin)/(dx*dy) * nlyrs(nn,mm)^2; % Fill index pixel-matrix with 
area-averaging (near interfaces) 
end 
end 

% Two-grid index matrix and interface averaging 
N.x = x; N.y = y; N.n = zeros(length(x), length(y)); 
N.n(2:2:end,2:2:end) = 
sqrt(npsq); % Fill denser two-
grid index matrix 
N.n(3:2:end-2,:) = sqrt( (N.n(2:2:end-3,:).^2 + N.n(4:2:end-
1,:).^2)/2 ); % Dielectric averaging between two pixels at 
interfaces 
N.n(:,3:2:end-2) = sqrt( (N.n(:,2:2:end-3).^2 + N.n(:,4:2:end-
1).^2)/2 ); 
N.n(1,:) = N.n(2,:); N.n(end,:) = N.n(end-1,:); N.n(:,1) = N.n(:,2); 
N.n(:,end) = N.n(:,end-1); 
end 

if(flagepsavg == 1) % More sophisticated index averaging - separate 
for each tensor component, arithmetic for parallel field, geometric 
for normal 
if(VMODE > 0) fprintf('Using "parallel-normal field" determined 
dielectric averaging.'\n'); end 
N.x = x; N.y = y; N.n = zeros(length(x), length(y)); 
% Better averaging (hopefully at most only 2 pixels shaded near any 
one interface) 
% Ez dielectric const averaging (x -> arithmetic, y -> arithmetic) 
xp = x(1:2:end); yp = y(1:2:end); npsqz = zeros(length(xp), 
length(yp));
for mm = 1:MM
    % along x-coordinate
    ixin = find((xp+dx/2) > xint(mm) & (xp-dx/2) <= xint(mm+1));
    % Find all pixels with at least some part inside region (mm,nn)
    xpmin = max(xint(mm), xp(ixin)-dx/2);  xpmax = min(xint(mm+1), xp(ixin)+dx/2);
    % Min and max coords of pixel *in* region (mm,nn)
    for nn = 1:NN
        % along y-coordinate
        iyin = find((yp+dy/2) > yint(nn) & (yp-dy/2) <= yint(nn+1));
        ypmin = max(yint(nn), yp(iyin)-dy/2);  ypmax = min(yint(nn+1), yp(iyin)+dy/2);
        % Min and max coords of pixel *in* region (mm,nn)

        npsqz(ixin,iyin) = npsqz(ixin,iyin) + (xpmax-xpmin).*(ypmax-ypmin)/(dx*dy) * nlyrs(nn,mm)^2;
        % Fill index pixel-matrix with area-averaging (near interfaces)
    end
end
warning off MATLAB:divideByZero

% Ey dielectric const averaging (first y -> geometric, then x -> arithmetic)
xp = x(1:2:end); yp = y(2:2:end-1); npsqy = Inf * ones(length(xp), length(yp)); npsqytot = zeros(length(xp), length(yp));
for mm = 1:MM
    % along x-coordinate
    ixin = find((xp+dx/2) > xint(mm) & (xp-dx/2) <= xint(mm+1));
    % Find all pixels with at least some part inside region (mm,nn)
    xpmin = max(xint(mm), xp(ixin)-dx/2);  xpmax = min(xint(mm+1), xp(ixin)+dx/2);
    % Min and max coords of pixel *in* region (mm,nn)
    for nn = 1:NN
        % along y-coordinate
        iyin = find((yp+dy/2) > yint(nn) & (yp-dy/2) <= yint(nn+1));
        ypmin = max(yint(nn), yp(iyin)-dy/2);  ypmax = min(yint(nn+1), yp(iyin)+dy/2);
        % Min and max coords of pixel *in* region (mm,nn)

        npsqy(ixin,iyin) = 1./(1./npsqy(ixin,iyin) + 1./((xpmax-xpmin).*(1./(ypmax-ypmin))/(dx*dy) * nlyrs(nn,mm)^2));
        % Fill index pixel-matrix with area-averaging (near interfaces)
    end
end

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npsqy(find(~isfinite(npsqy))) = 0;
npsqytot = npsqytot + npsqy;  % Fill index pixel-matrix with
area-averaging (near interfaces)
npsqy = Inf * ones(length(xp), length(yp));
end
% Ex dielectric const averaging (first x ~> geometric, then y ~> arithmetic)
xp = x(2:2:end-1); yp = y(1:2:end); npsqx = Inf * ones(length(xp), length(yp));
npsqxtot = zeros(length(xp), length(yp));
for nn = 1:NN
  % along y-coordinate
  iyin = find((yp+dy/2) > yint(nn) & (yp-dy/2) <= yint(nn+1));
  ypin = max(yint(nn), yp(iyin)-dy/2);  ypm = min(yint(nn+1),
  yp(iyin)+dy/2);  % Min and max coords of pixel *in* region (mm,nn)
  for mm = 1:MM
    % along x-coordinate
    ixin = find((xp+dx/2) > xint(mm) & (xp-dx/2) <=
    xint(mm+1));  % Find all pixels with at least some
    part inside region (mm,nn)
    xpm = max(xint(mm), xp(ixin)-dx/2);  xpm = min(xint(mm+1),
    xp(ixin)+dx/2);  % Min and max coords of pixel *in* region (mm,nn)

    npsqx(ixin,iyin) = 1./(1./npsqx(ixin,iyin) + 1./(1./(xpmax
    -xpin).*(ypmax-ypm)))/(dy/dx) * nlyrs(nn,mm)^2));  % Fill index
pixel-matrix with area-averaging (near interfaces)
  end
  npsqx(find(~isfinite(npsqx))) = 0;
npsqxtot = npsqxtot + npsqx;  % Fill index pixel-matrix with
area-averaging (near interfaces)
npsqx = Inf * ones(length(xp), length(yp));
end
warning on MATLAB:divideByZero
% Combine tensor components into full index distribution:
N.n(1:2:end,1:2:end) = sqrt(npsqz); N.n(1:2:end,2:2:end-1) =
sqrt(npsqytot); N.n(2:2:end-1,1:2:end) = sqrt(npsqxtot);
% Index components on below line should really not matter! and should
be NaN, but they *seem* to be used, perhaps in PMLs (coord stretch)
so I set them here
N.n(2:2:end-1,2:2:end-1) = sqrt((N.n(1:2:end-2,2:2:end-1).^2 +
N.n(3:2:end,2:2:end-1).^2 + N.n(2:2:end-1,1:2:end-2).^2 +
N.n(2:2:end-1,3:2:end).^2)/4);
if(find(~isfinite(N.n))) error('sisolver3d error'); end

if(nargout > 1)  % If modes are also desired (F output parameter asked), then call modesolver

% Process horizontal or vertical electric or magnetic wall symmetries
(OPTS.vsymm = 'E','M')
if(isfield(OPTS,'vsymm'))  % Asking for any vertical symmetries?
    if(VMODE>0) fprintf('Symmetry condition specified is...: '); end
    switch lower(OPTS.vsymm)
        case 'm'  % Vertical magnetic wall at y = 0 (USER MUST ENSURE MIDDLE LAYER HAS ODD # OF PIXELS!)
            if(VMODE>0) fprintf('Magnetic wall (at half pixel steps) vertical symmetry.\n'); end
            iy = find(N.y > max(N.y)/2 -(dy/2 * 1.001));
            N.y = N.y(iy); N.n = N.n(:,iy);
            OPTS.BC(3) = 1;  % Set magnetic wall at bottom
        case 'e'  % Vertical electric wall at y = 0 (USER MUST ENSURE MIDDLE LAYER HAS EVEN # OF PIXELS!)
            if(VMODE>0) fprintf('Electric wall (at full pixel steps) vertical symmetry.\n'); end
            iy = find(N.y > max(N.y)/2 -(dy/2 * 0.001));
            N.y = N.y(iy); N.n = N.n(:,iy);
            OPTS.BC(3) = 0;  % Set electric wall at bottom
        otherwise
            if(VMODE>0) fprintf('unknown (''%s''). ERROR.\n', OPTS.vsymm); end
            error('[MP] sisolver3d - unknown symmetry condition specified');
    end
end

if(isfield(OPTS,'hsymm'))  % Asking for any vertical symmetries?
    if(VMODE>0) fprintf('Symmetry condition specified is...: '); end
    switch lower(OPTS.hsymm)
        case 'm'  % Horizontal magnetic wall at x = 0 (USER MUST ENSURE MIDDLE LAYER HAS ODD # OF PIXELS!)
            if(VMODE>0) fprintf('Magnetic wall (at half pixel steps) horizontal symmetry.\n'); end
            ix = find(N.x > max(N.x)/2 -(dx/2 * 1.001));
            N.x = N.x(ix); N.n = N.n(ix,:);
            OPTS.BC(1) = 1;  % Set magnetic wall at left
        case 'e'  % Horizontal electric wall at x = 0 (USER MUST ENSURE MIDDLE LAYER HAS EVEN # OF PIXELS!)
            if(VMODE>0) fprintf('Electric wall (at full pixel steps) horizontal symmetry.\n'); end

if (VMODE > 0) fprintf('Electric wall (at full pixel steps) horizontal symmetry.\n'); end
ix = find(N.x > max(N.x)/2 - (dx/2 * 0.001));
N.x = N.x(ix); N.n = N.n(ix,:);
OPTS.BC(1) = 0; % Set electric wall at left

otherwise
if (VMODE > 0) fprintf('unknown (''%s''). ERROR.\n', OPTS.hsymm); end
error('[MP] sisolver3d - unknown symmetry condition specified');
end

% For bend modes:
if (nargin > 5) & isfield(OPTS,'radius');
    R = OPTS.radius; N.x = N.x + R; % Set left edge of domain to be at radius
    if (VMODE > 0) fprintf([mfilename ': Using radius of %g um at LEFT EDGE of the computational domain.\n'], R); end
    % mu_guess = mu_guess * R; % Reset eigenvalue
    OPTS.coordmode = 'R';
    PMLwidth = [0 0.5 0 0]; PMLsigma = [0.1 0.1]; % um, um^-1
end
if ~isfield(OPTS,'PMLwidth')
    OPTS.PMLwidth = PMLwidth; OPTS.PMLsigma = PMLsigma;
end

um = 1;
if (isfield(OPTS,'enginever'))
    if (VMODE > 0) disp(['Calling solver engine ' OPTS.enginever '.']); end
    [beta, F, V] = feval(OPTS.enginever, N, k0, mu_guess, OPTS, NMODES_CALC, OPTS.PMLwidth, OPTS.PMLsigma); % Call custom solver
else
    if (VMODE > 0) disp('Calling default engine (m2wcyl).'); end
    [beta, F, V] = m2wcyl(N, k0, mu_guess, OPTS, NMODES_CALC, OPTS.PMLwidth, OPTS.PMLsigma); % Call default solver
end

alpha = imag(beta);

% Anatoly changed dBcm calculation here
F.dBcm = 20/log(10) * alpha*1e4; % Store any loss in dB/cm
if isfield(OPTS,'radius')
F.dBcm = F.dBcm/OPTS.radius;  % factor out the radius which is included into beta;
end;

F.beta = beta;
warning off MATLAB:divideByZero;

F.LossQ = real(beta)./imag(beta)/2;

warning on MATLAB:divideByZero;
% Remove undesired modes
F.Ex = F.Ex(:,:,1:NMODES_KEEP); F.Ey = F.Ey(:,:,1:NMODES_KEEP); F.Ez = F.Ez(:,:,1:NMODES_KEEP);
F.Hx = F.Hx(:,:,1:NMODES_KEEP); F.Hy = F.Hy(:,:,1:NMODES_KEEP); F.Hz = F.Hz(:,:,1:NMODES_KEEP);
F.dx = dx; F.dy = dy;
end

F.k0 = k0;

(b) Pump/signal mode overlap calculation

function Olap = 
Strt_wvg_pumpOlap_Er_Tm(sig,pump,Gnum,Sn_guideW,Ox_gap_W,AlO_H,Sn_guideH,dp_W,dp_gap,flg,flgs)
%% INPUTS:
%  sig = signal wavelength [um]
%  pump = pump wavelength [um]
%  Gnum = number of nitride pieces below trench
%  Sn_guideW = width of nitride pieces
%  Ox_gap_W = width of oxide gap between nitride pieces
%  AlO_H = height of aluminum oxide layer
%  Sn_guideH = height of nitride layer
%  dp_W = width of dispersion blocks (put 0 if not used)
%  dp_gap = spacing of dispersion blocks (put 0 if not used)
%  flg = 1 if using dispersion blocks, 0 otherwise
%  flgs = 1 if generating a save file for use in gain codes, 0 otherwise

%% OUTPUTS:
%  Olap = intensity overlap (in the gain material) between signal and pump modes
% Part 1: set material parameters
a = 1.70677; b = 0.01921; c = 0; d = 0; e = 0; f = 0; % best case
% a = 1.6419; b = 0.04081; c = 0.02424; d = 0; e = 0.02424; f = 0; % worst case

% fit for oxide is taken from the literature.
C1Ox = 0.6961663; C2Ox = 0.4079426; C3Ox = 0.8974794;
L1Ox = 0.0684043; L2Ox = 0.1162414; L3Ox = 9.896161;

% V1 Nitride:
% C1N = 2.911; C2N = 0.02083; L1N = 0.01739; L2N = 0.07433;

% "New6" Nitride:
C1N = 2.745634; C2N = 0.021544; L1N = 0.039982; L2N = 0.078486;

% Part 2: set geometric parameters

% set layer thicknesses
Ox_gap_H = 0.2;
Air_H = 2.0;
% assume bottom oxide arbitrarily thick.
% set vertical grid height
step_h = 0.05; % um
% set vertical grid:
height = [3.0 SiN_guideH Ox_gap_H AlO_H Air_H];

% set horizontal grid:
step_w = 0.05;

w_tr = 40.0;
if flg
    Side_space = (w_tr-2*(dp_W+dp_gap)-(Gnum*SiN_guideW+(Gnum-1)*Ox_gap_W))/2;
    width = [5.0, Side_space, dp_W, dp_gap];
    for ij = 1:1:Gnum-1
        width(ij*2+3) = SiN_guideW;
        width(ij*2+4) = Ox_gap_W;
    end
    width = [width, SiN_guideW, dp_gap, dp_W, Side_space];
else
    Side_space = (w_tr-(Gnum*SiN_guideW+(Gnum-1)*Ox_gap_W))/2;
    width = [5.0, Side_space];
    for ij = 1:1:Gnum
        width(ij*2+1) = SiN_guideW;
end

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width(ij*2+2) = Ox_gap_W;
end
width(end) = Side_space;
end
width = [width, 5.0];

%% Part 3: set simulation parameters

% set numeric parameters
dxy = [step_w step_h];  % step size; steps that end on medium boundaries yield better precision
options.NMODES_CALC = 1;  % how many modes to calculate
options.PMWidth = [0 0.0 0.0 0.0];  % left right bottom top; we don't need PMLs for straight guide
options.PMLsigma = [0.3 0.3];
% options.hsymm = 'e';

%% Part 4: run simulation
mlam = sig;

% determine index value for current wavelength
n_SiO2 = sqrt(1+C1Ox*mlam^2/(mlam^2-L1Ox^2)+C2Ox*mlam^2/(mlam^2-L2Ox^2)+C3Ox*mlam^2/(mlam^2-L3Ox^2))
n_SiN = sqrt(1+C1N*mlam^2/(mlam^2-L1N)+C2N*mlam^2/(mlam^2-L2N))
n_Eglass = sqrt(1+a*mlam^2/(mlam^2-b)+c*mlam^2/(mlam^2-d)+e*mlam^2/(mlam^2-f))
n_clad = 1.0;

% create index structures with those values
n = [n_SiO2, n_SiO2;...   
n_SiO2, n_SiO2;...   
n_SiO2, n_SiO2;...   
n_SiO2, n_Eglass;...   
n_SiO2, n_clad];

if flg
  Gnum2 = Gnum+2;
else
  Gnum2 = Gnum;
end
for jk = 1:1:Gnum2
  nadd = [n_SiO2    n_SiO2;... 
n_SiN      n_SiO2;...   
n_SiO2    n_SiO2;...   
n_Eglass  n_Eglass;...]
n_clad     n_clad];
    n = [n, nadd];
end
nadd = [n_SiO2; n_SiO2; n_SiO2; n_SiO2; n_SiO2];
n = [n, nadd];

k0 = 2*pi/mlam;
options.mu_guess = k0*1.6; %guess for beta
tic;
[N,F] = sisolver3d(n, width, height, dxy, k0, options);
PlotModes(F);

% Now do the pump
mlam = pump;

%determine index value for current wavelength
n_SiO2  = sqrt(1+C1Ox*mlam^2/(mlam^2-L1Ox^2)+C2Ox*mlam^2/(mlam^2-
L2Ox^2)+C3Ox*mlam^2/(mlam^2-L3Ox^2))
n_SiN   = sqrt(1+C1N*mlam^2/(mlam^2-L1N)+C2N*mlam^2/(mlam^2-L2N))
n_Eglass = sqrt(1+a*mlam^2/(mlam^2-b)+c*mlam^2/(mlam^2-
d)+e*mlam^2/(mlam^2-f))
n_clad = 1.0;

%create index structures with those values
n = [n_SiO2, n_SiO2;... n_SiO2, n_SiO2;... n_SiO2, n_SiO2;... n_SiO2, n_Eglass;... n_SiO2, n_clad];
for jk = 1:1:Gnum2
    nadd = [n_SiO2     n_SiO2;... n_SiN     n_SiO2;... n_SiO2     n_SiO2;... n_Eglass n_Eglass;... n_clad     n_clad];
    n = [n, nadd];
end
nadd = [n_SiO2; n_SiO2; n_SiO2; n_SiO2; n_SiO2];
n = [n, nadd];

k0 = 2*pi/mlam;
options.mu_guess = k0*1.68;
[~,F_p] = sisolver3d(n, width, height, dxy, k0, options);
PlotModes(F_p)
toc;

disp('finished mode calculation')

Ex = F.Ex;
mloc2 = find(abs(Ex) == max(max(abs(Ex))));
ang1 = angle(Ex(mloc2));
F.Ex = F.Ex*exp(-1i*ang1);
F.Ey = F.Ey*exp(-1i*ang1);
F.Hx = F.Hx*exp(-1i*ang1);
F.Hy = F.Hy*exp(-1i*ang1);

Ex = F_p.Ex;
mloc2 = abs(Ex) == max(max(abs(Ex)));
ang1 = angle(Ex(mloc2));
F_p.Ex = F_p.Ex*exp(-1i*ang1);
F_p.Ey = F_p.Ey*exp(-1i*ang1);
F_p.Hx = F_p.Hx*exp(-1i*ang1);
F_p.Hy = F_p.Hy*exp(-1i*ang1);

%alternative calculation for TE modes:
Nn = N.n;
Nn = Nn(3:2:end, 3:2:end) + Nn(3:2:end, 2:2:end) + Nn(2:2:end, 3:2:end) + Nn(2:2:end, 2:2:end);
Nn = Nn/4;
mask_pane = ((Nn(:,1:end-1) > n_Eglass*.98) & (Nn(:,1:end-1) < n_Eglass*1.02));
norm1 = abs(sum(sum(F_p.Ex.*conj(F_p.Ex))*dxy(1)*dxy(2))^2;
norm2 = abs(sum(sum(F.Ex.*conj(F.Ex)))*dxy(1)*dxy(2))^2;
nu = abs(sum(sum(F.Ex.*conj(F.p.Ex).*mask_pane))*dxy(1)*dxy(2))^2;
Olap = nu/sqrt(norm1*norm2);
disp(['Olap = ', num2str(Olap)]);

%% Save mode profiles
if flgs
[~,signal_mode_profile,~] = ecrosshdotz(F,F,1,1);
[~,pump_mode_profile,~] = ecrosshdotz(F_p,F_p,1,1);
DX = step_w;
DY = step_h;
NNlogic = mask_pane;
filename = 'amplifier_mode_profiles.mat';
save(filename,'signal_mode_profile','pump_mode_profile','DX','DY','NN_logic')
end
end

(c) Amplification calculation based on rate equation

% Doped aluminum oxide amplifier simulation
% Analytical steady state solution to rate equations based on 3-level approximation
% Pump and signal intensity profiles determined separately by modesolver
% (simplified 3-level model without CR or ETU processes)
%====================================================================
function P_s_out = Tm_wvg_1610_amplifier_modification_NX_4(P_in_s, P_in_p)
tic;
%====================================================================
%Constants
h = 6.626068e-34; %Planck's constant [m^2kg/s]
c = 299792458.; %Speed of light [m/s]
e = 2.718281828; %e
%====================================================================
%Define pump and signal beams and active medium dimensions
L = 2; % cavity length (in cm)
wl_s = 1900; %dlmread('Cross_Sections.txt', '\t','A1..A301'); %Signal wavelengths [nm]
wl_p = 1610; %Pump wavelength [nm]
num_Pinp = 1;
type_beam = 2; %0=flat-
num_Z = 20; %Number of discretizations in the longitudinal direction
dZ = L/num_Z; %Longitudinal filename = 'amplifier_mode_profiles_t_1p4.mat';
%====================================================================

%Define material and spectroscopic properties

% 0 = 3-level analytical solutions (no fast quenching), 1 = 3-level solved by Matlab ODE (including fast quenching)

% alpha_s = 1.75; %Signal background loss [dB/cm]
alpha_s = 0.7;
a_s = alpha_s/4.34294482; %Signal background loss coefficient [cm^-1]

% alpha_p = 1.0; %Pump background loss [dB/cm]
alpha_p = 0.7; %Pump background loss coefficient coefficient [cm^-1]

N_Tm = 3.0e20; %Thulium ion concentration [cm^-3]

% sigma_01 = 0.4e-21; %Signal absorption cross sections [cm^2]
sigma_01 = 2.7e-21;

% sigma_10 = 2.7e-21; %Signal emission cross sections [cm^2]

% tau_10 = 0.2e-3; %First excited state lifetime [s]
tau_10 = 550e-6;

% sigma_02 = 3.5e-21; %Pump absorption cross section [cm^2]
sigma_02 = 2.4e-21;

% tau_21 = 15.0e-6; %Second excited state lifetime [s]

% User-defined profile:

if type_beam==2
load(filename);
end

% Load values from signal intensity profile file
P_norm_s = 
(1/sum(sum(signal_mode_profile))).*signal_mode_profile; %Create normalized signal intensity profile from Poynting vector

P_norm_p = 
(1/sum(sum(pump_mode_profile))).*pump_mode_profile; %Create normalized pump intensity profile from Poynting vector

num_X = length(P_norm_s(:,1)); %Number of discretizations in the X direction
%Number of discretizations in the Y direction
num_Y = length(P_norm_s(1,:));

% X step
DX = DX;

dX = DX;

% Y step
DY = DY;

% Size of each mesh element [\text{m}]
dA = zeros(num_X,num_Y);

dA(:,:) = dX * dY;

% Area of each mesh element [\text{m}^2]

region_active = NNlogic
end

%====================================================================

%====================================================================

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Initialize arrays for storing pump and signal power and gain
P_total_s = zeros(num_Z + 1, num_Pinp); % Initialize total signal power at each launched pump power, wavelength and z-step
P_total_p = zeros(num_Z + 1, num_Pinp); % Initialize total pump power at each launched pump power, wavelength and z-step
P_s = zeros(num_X, num_Y, num_Z + 1, num_Pinp); % Initialize signal power at each coordinate in the waveguide
P_p = zeros(num_X, num_Y, num_Z + 1, num_Pinp); % Initialize pump power at each coordinate in the waveguide
phi_s = zeros(num_X, num_Y, num_Z, num_Pinp); % Initialize signal photon flux at each coordinate in the waveguide
phi_p = zeros(num_X, num_Y, num_Z, num_Pinp); % Initialize pump photon flux at each coordinate in the waveguide
CONST = zeros(num_X, num_Y, num_Z, num_Pinp);
N_0 = N_Tm.*ones(num_X, num_Y, num_Z, num_Pinp); % Initialize ground state population density matrix [cm^{-3}]
N_1 = zeros(num_X, num_Y, num_Z, num_Pinp); % Initialize 4I13/2 level population density matrix [cm^{-3}]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% 1) Start outer loop for incrementing pump power

% % for index_Pinp = 1:num_Pinp
index_Pinp = 1;

% Initialize signal and pump powers and photon fluxes and population densities at each coordinate in the waveguide
P_total_s(1,index_Pinp) = P_in_s;
P_total_p(1,index_Pinp) = P_in_p(index_Pinp);
P_s(:,:,1,index_Pinp) = P_in_s.*P_norm_s;
P_p(:,:,1,index_Pinp) = P_in_p(index_Pinp).*P_norm_p;
%2) Start loop for determining power along amplifier length
%Propagate in Z direction, solving population equations for each
%Z step: fill signal and pump arrays at each step, redistributing
%the total power in a Gaussian profile.
for index_Z=1:num_Z

if type_solver==0

%Determine photon fluxes (in cm^-2):
phi_s(:,:,index_Z,index_Pinp) = P_s(:,:,index_Z,index_Pinp).*1e-3.*wl_s.*1e-9./(dA(:,:,)*1e-12*h*c)*1e-4;
phi_p(:,:,index_Z,index_Pinp) = P_p(:,:,index_Z,index_Pinp).*1e-3.*wl_p.*1e-9./(dA(:,:,)*1e-12*h*c)*1e-4;

%Solve for population densities:
CONST(:,:,index_Z,index_Pinp) = tau_10*phi_s(:,:,index_Z,index_Pinp)*sigma_10+1;
N_0(:,:,index_Z,index_Pinp) = (CONST(:,:,index_Z,index_Pinp)*N_Tm./(tau_10*(phi_p(:,:,index_Z,index_Pinp)*sigma_02+phi_s(:,:,index_Z,index_Pinp)*sigma_01)...+
CONST(:,:,index_Z,index_Pinp))).*region_active(:,:,);
N_1(:,:,index_Z,index_Pinp) = (N_Tm-N_0(:,:,index_Z,index_Pinp)).*region_active(:,:,);

%Determine powers remaining after propagation through Z-step in
%each element and keep running total of total power remaining
%after Z-step
P_s(:,:,index_Z+1,index_Pinp) = P_s(:,:,index_Z,index_Pinp).*e.^((-sigma_10.*N_1(:,:,index_Z,index_Pinp)-sigma_01.*N_0(:,:,index_Z,index_Pinp)-a_s).*dZ);
P_p(:,:,index_Z+1,index_Pinp) = P_p(:,:,index_Z,index_Pinp).*e.^((-sigma_02.*N_0(:,:,index_Z,index_Pinp)-a_p).*dZ);

%Determine total pump and signal powers and total signal gamma
%after propagating through Z-step. Establish signal and pump
%power arrays for input into the next section by redistributing
%the power in the mode distribution.
P_total_s(index_Z+1,index_Pinp) = sum(sum(P_s(:,:,index_Z+1,index_Pinp)));  
P_total_p(index_Z+1,index_Pinp) = sum(sum(P_p(:,:,index_Z+1,index_Pinp)));  
%gamma(index_Z+1,index_Pinp)=10.*log10(P_total_s(index_Z+1,index_Pinp)/
P_total_s(1,index_Pinp));
P_s(:,:,index_Z+1,index_Pinp)=P_total_s(index_Z+1,index_Pinp).*P_norm_s;
P_p(:,:,index_Z+1,index_Pinp)=P_total_p(index_Z+1,index_Pinp).*P_norm_p;
end %End Z-propagation loop (2)

% % end %End loop for incrementing launched pump power (1)
%====================================================================
=====
%Plotting
P_s_out=P_total_s(end,1);
toc;
%====================================================================
=====

(d) Lasing power calculation (DBR cavity)

%close all; clear all;
% Tm_wvg_790_pump_laser

function Tm_wvg_1610_pump_laser_sweep_output_reflectivity
% Laser device parameters
R1=0.9991;  %pump input side mirror reflectivity
R2=0.6;   %output mirror reflectivity
R2_min=0.50;
R2_max=0.70;
R2_interval=0.01;
R2=R2_min:R2_interval:R2_max;
R2_index=(R2_max-R2_min)/R2_interval+1;
%P_in_s = 1e-3;  %initial signal power (mW)
P_in_s = 0.02;
%define pump power
P(1:50) = P_in_s;
%P_in_p(1:Pump_index) = 0:Pump_interval:Pump_max;

Pump_index=1;

P_in_p=1000;

for k=1:R2_index

    for j=1:Pump_index

        for i=1:50

end
end %End Z-propagation loop (2)

% % end %End loop for incrementing launched pump power (1)
%====================================================================
=====
%Plotting
P_s_out=P_total_s(end,1);
toc;
%====================================================================
=====

(d) Lasing power calculation (DBR cavity)
P(i+1) =
R2(k) * Tm_wvg_1610_amplifier_modification_NX_4(P(i), P_in_p(j));
% forward propagation and 1st reflection
P(i+1) =
R1 * Tm_wvg_1610_amplifier_modification_NX_4(P(i+1), P_in_p(j));
% backward propagation and 2nd reflection

if (P(i+1) - P(i))/P(i) < 1e-3
    if (P(i+1) - P(i))/P(i) < 5e-3
        break;
    else
        end
end
Pout(j) = max(P(i));
end

Output_power(k) = Pout * (1 - R2(k))
end

figure;
plot(R2, Output_power);
Appendix III Matlab Code for Grating

The simulation codes for grating are listed below. There are three parts: (a) 2D mode solver; (b) gain waveguide simulation with gratings as perturbation; and (c) grating response calculation. Code (a) is modified based on PhD thesis of Thomas Murphy [101]. It has to be in the same folder as the code (b). The gain waveguide structure is defined in code (b) which calls code (a). It calculates out the effective index ($n_{eff}$) and coupling coefficient of the grating ($\kappa$). Then the grating response for either DFB or DBR can be calculated by substituting the obtained $n_{eff}$ and $\kappa$ into code (c).

(a) 2D Mode solver

```
function [phi,neff] = svmodes (lambda, guess, nmodes, dx, dy, ...
    eps, boundary, field);

% INPUT:
%
% lambda - optical wavelength
% guess - scalar shift to apply when calculating the eigenvalues.
%   This routine will return the eigenpairs which have an
%   effective index closest to this guess
% nmodes - the number of modes to calculate
% dx - horizontal grid spacing
% dy - vertical grid spacing
% eps - index mesh (= n^2(x,y))
% boundary - 4 letter string specifying boundary conditions to be
%   applied at the edges of the computation window.
% boundary(1) = North boundary condition
% boundary(2) = South boundary condition
% boundary(3) = East boundary condition
% boundary(4) = West boundary condition
% The following boundary conditions are supported:
% 'A' - field is antisymmetric
% 'S' - field is symmetric
% '0' - field is zero immediately outside of the
%       boundary.
% field - must be 'EX', 'EY', or 'scalar'
%
% OUTPUT:
```
% phi - three-dimensional vector containing the requested
% field component for each computed mode
% neff - vector of modal effective indices

boundary = upper(boundary);

[nx,ny] = size(eps);

eps = [eps(:,1),eps,eps(:,ny)];
eps = [eps(1,:), eps(:, ny), eps(nx,:)];

k = 2*pi/lambda;

if iscalar(dx)
    dx = dx*ones(nx+2,1);
else
    dx = dx(:);
    dx = [dx(1);dx;dx(length(dx))];
end

if iscalar(dy)
    dy = dy*ones(1,ny+2);
else
    dy = dy(:);
    dy = [dy(1);dy;dy(length(dy))].';
end

n = ones(1,nx*ny); n(:) = ones(nx,1)*(dy(3:ny+2)+dy(2:ny+1))/2;
s = ones(1,nx*ny); s(:) = ones(nx,1)*(dy(1:ny)+dy(2:ny+1))/2;
e = ones(1,nx*ny); e(:) = (dx(3:nx+2)+dx(2:nx+1))/2*ones(1,ny);
w = ones(1,nx*ny); w(:) = (dx(1:nx)+dx(2:nx+1))/2*ones(1,ny);
p = ones(1,nx*ny); p(:) = dx(2:nx+1)*ones(1,ny);
q = ones(1,nx*ny); q(:) = ones(nx,1)*dy(2:ny+1);

en = ones(1,nx*ny); en(:) = eps(2:nx+1,3:ny+2);
es = ones(1,nx*ny); es(:) = eps(2:nx+1,1:ny);
ee = ones(1,nx*ny); ee(:) = eps(3:nx+2,2:ny+1);
ew = ones(1,nx*ny); ew(:) = eps(1:nx,2:ny+1);
ep = ones(1,nx*ny); ep(:) = eps(2:nx+1,2:ny+1);

switch lower(field)
    case 'ex'
        an = 2./n./(n+s);
        as = 2./s./(n+s);
ae = 8*(p.*(ep-ew)+2.*w.*ew).*ee./
  ((p.*(ep-ee)+2.*e.*ee).*p.^2.*(ep-ew)+4.*w.^2.*ew) + ... 
  (p.*(ep-ew)+2.*w.*ew).*p.^2.*(ep-ee)+4.*e.^2.*ee));
aw = 8*(p.*(ep-ee)+2.*e.*ee).*ew./
  ((p.*(ep-ee)+2.*e.*ee).*p.^2.*(ep-ew)+4.*w.^2.*ew) + ...
  (p.*(ep-ee)+2.*w.*ew).*p.^2.*(ep-ee)+4.*e.^2.*ee));
ap = ep.*k^2 - an - as - ae.*ep./ee - aw.*ep./ew;
case 'ey'
an = 8*(q.*(ep-es)+2.*s.*es).*en./
  ((q.*(ep-en)+2.*n.*en).*q.^2.*(ep-es)+4.*s.^2.*es) + ...
  (q.*(ep-es)+2.*s.*es).*q.^2.*(ep-en)+4.*n.^2.*en});
as = 8*(q.*(ep-en)+2.*n.*en).*es./
  ((q.*(ep-en)+2.*n.*en).*q.^2.*(ep-es)+4.*s.^2.*es) + ...
  (q.*(ep-es)+2.*s.*es).*q.^2.*(ep-en)+4.*n.^2.*en});
ae = 2./e./(/e+w);
aw = 2./w./(/e+w);
ap = ep.*k^2 - an.*ep./en - as.*ep./es - ae - aw;
case 'scalar'
an = 2./n./(/n+s);
as = 2./s./(/n+s);
ae = 2./e./(/e+w);
aw = 2./w./(/e+w);
ap = ep.*k^2 - an - as - ae - aw;
end
ii = zeros(nx,ny);
ii(1) = (1:nx*ny); % north boundary
ib = zeros(1,nx);
ib(1) = ii(1:nx,ny);
if (boundary(1) == 'S')
ap(ib) = ap(ib) + an(ib);
elseif (boundary(1) == 'A')
ap(ib) = ap(ib) - an(ib);
end
% south boundary
ib = zeros(1,nx);
ib(1) = ii(1:nx,1);
if (boundary(2) == 'S')
ap(ib) = ap(ib) + as(ib);
elseif (boundary(2) == 'A')
    ap(ib) = ap(ib) - as(ib);
end

% east boundary
ib = zeros(1, ny);
ib(:) = ii(nx, 1:ny);
if (boundary(3) == 'S')
    ap(ib) = ap(ib) + ae(ib);
elseif (boundary(3) == 'A')
    ap(ib) = ap(ib) - ae(ib);
end

% west boundary
ib = zeros(1, ny);
ib(:) = ii(1, 1:ny);
if (boundary(4) == 'S')
    ap(ib) = ap(ib) + aw(ib);
elseif (boundary(4) == 'A')
    ap(ib) = ap(ib) - aw(ib);
end

iall = zeros(1, nx*ny); iall(:) = ii;
in = zeros(1, nx*(ny-1)); in(:) = ii(1:nx, 2:ny);
is = zeros(1, nx*(ny-1)); is(:) = ii(1:nx, 1:(ny-1));
ie = zeros(1, (nx-1)*ny); ie(:) = ii(2:nx, 1:ny);
iw = zeros(1, (nx-1)*ny); iw(:) = ii(1:(nx-1), 1:ny);

A = sparse ([iall, iw, ie, is, in], ...  
            [iall, ie, iw, in, is], ...  
            [ap(iall), ae(iw), aw(ie), an(is), as(in)]);

shift = (2*pi*guess/lambda)^2;
options.tol = 1e-8;
options.disp = 0;
options.isreal = isreal(A);

[phi, d] = eigs(A, speye(size(A)), nmodes, shift, options);
neff = lambda*sqrt(diag(d))/(2*pi);

phi = zeros(nx, ny, nmodes);
temp = zeros(nx,ny);

for k = 1:nmodes;
    temp(:) = v(:,k)/max(abs(v(:,k)));
    phi(:,:,k) = temp;
end;

(b) Gain waveguide simulation with gratings as perturbation

function kappa = grating(wgw_grating)

nm = 1e-9;
um = 1e-6;
c = 2.99792458e8;

%Grating parameters
D = 1.0;

% index based on V6
% Refractive indices:
% for signal
n_Air = 1.00;

% SiO2 Insulator
n_lowerSiO2 = 1.444;

% Phosphide Galss Core Al2O3
n_Al2O3 = 1.651;

% SiN
n_SiN = 1.94;

% Upper cladding (air)

% Grating region
n_Grating = sqrt(D*n_SiN^2+(1-D)*n_lowerSiO2^2)

% Layer heights:
% SiO2 Insulator thickness
h_lowerSiO2 = 3.0;

% SiN Thickness
h_SiN = 0.20;

% P-glass thickness
h_Al2O3 = 1.20;

% SiO2
h_upperSiO2 = 0;

% air
h_air = 1.0;

% air
vgap = 0.2;

gap = 0.35;
gap_grating = 0.35;

wgw = 0.3; % SiN width
pitch_wg = gap + wgw;

wgw_grating = 0.30; % grating width for DFB, not for DBR
pitch_wg_grating = gap_grating + wgw/2 + wgw_grating/2; % for DFB, not for DBR

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side = 10; % Space on side

dx = 0.02; % grid size (horizontal)
dy = 0.02; % grid size (vertical)
lambda = 1.88;

nmodes = 1; % number of modes to compute

boundary = '000S'; % boundary condition

xmin = 0;
xmax = 2*side+5*pitch_wg+2*pitch_wg_grating+2;
ymin = 0;
ymax = h_lowerSiO2+h_Al2O3+h_upperSiO2+h_air;

[x, y, xc, yc, nx, ny, eps] = diel([xmin xmax ymin ymax], dx, dy);

%% dielectric structure
eps = n_lowerSiO2^2*eps;
eps(:, yc<=h_lowerSiO2) = n_lowerSiO2^2;

%%% normal trench
eps(xc>xmax/2-1 & xc<xmax/2-1 & yc=h_lowerSiO2 & yc<=h_lowerSiO2+h_Al2O3) = n_A2O3^2;

%% no trench
eps(xc>xmax/2 & xc<xmax/2 & yc=h_lowerSiO2 &
yc<=h_lowerSiO2+h_Al2O3) = n_A2O3^2;

eps(:, yc=h_lowerSiO2+h_A2O3) = n_upperSiO2^2;
eps(:, yc=h_lowerSiO2+h_A2O3+h_upperSiO2) = 1;

%%% 5 wg and 7 Grating structure
eps(xc>=-wgw/2-3*pitch_wg & xc<=wgw/2-3*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_Grating^2;
eps(xc>=-wgw/2-2*pitch_wg & xc<=wgw/2-2*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_SiN^2;
eps(xc>=-wgw/2-1*pitch_wg & xc<=wgw/2-1*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_SiN^2;
eps(xc>=-wgw/2 & xc<=wgw/2, yc=h_lowerSiO2-vgap-h_SiN &
yc=h_lowerSiO2-vgap) = n_SiN^2;
eps(xc>=-wgw/2+1*pitch_wg & xc<=wgw/2+1*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_SiN^2;
eps(xc>=-wgw/2+2*pitch_wg & xc<=wgw/2+2*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_SiN^2;
eps(xc>=-wgw/2+3*pitch_wg & xc<=wgw/2+3*pitch_wg, yc=h_lowerSiO2-vgap-
h_SiN & yc=h_lowerSiO2-vgap) = n_Grating^2;
fprintf (1, 'generating index mesh...
');
[x, y, xc, yc, dx1, dy1] = stretchmesh(x, y, [0 0 0 0], [1 1 1 1]);

n_mesh = sqrt(abs(eps));

%% Plot the index profile
figure1 = figure('Color', [1 1 1]); % create a figure with white background
axes1 = axes('Parent', figure1, ...
    'FontWeight', 'bold', ...
    'FontSize', 24); % adjust font size for the axis
box(axes1, 'on'); grid(axes1, 'off'); hold(axes1, 'all');
imagemode(xc, yc, n_mesh/max(n_mesh(:)), dx, dy);
xlabel('Width /um');
ylabel('Height /um');

fprintf (1, 'solving for eigenmodes (TE) ... '); t = cputime;
[ExTE, neffTE] = svmodes(lambda, n_Al2O3, nmodes, dx1, dy1, eps, ... boundary, 'EX');
fprintf (1, 'done (cputime = %7.3f)
', cputime - t);
% fprintf(1,'neff(TE) = %2.7f+%2.7f
',real(neffTE));
disp(strcat('neff TE=', num2str(neffTE)));

%% Plot the mode profile
figure3 = figure('Color', [1 1 1]); % create a figure with white background
axes1 = axes('Parent', figure3, ...
    'FontWeight', 'bold', ...
    'FontSize', 24); % adjust font size for the axis
box(axes1, 'on'); grid(axes1, 'off'); hold(axes1, 'all');
imagemode(xc, yc, (ExTE/max(abs(ExTE(:))))^2, dx, dy);
[XC, YC] = meshgrid(xc, yc);
hold on;
contour(XC, YC, transpose(eps), [n_lowerSiO2^2 n_Al2O3^2 n_SiN^2], 'k', 'LineWidth', 1.0);
hold off;
xlabel('Width /um');
ylabel('Height /um');

%% Calculate overlap integrad
ExTE_G = ExTE(eps==n_Grating^2);
ExTE_A = zeros(1, nx*ny); % Ex in the whole area
ExTE_A(:) = ExTE(1:nx, 1:ny);
\[
\text{\textbf{(c) Grating response calculation for both DFB and DBR cavities}}
\]

% all the calculations are in meter
clear all; clc; close all;
lambda = 1e-6*linspace(1.8595, 1.8605, 100001);

neff = 1.5662;

lambda0 = 1.86e-6;
lambdaf = lambda0/2/real(neff) % period

kappa0 = 200;

i=1;
L_vector = 2e-2;

for L=L_vector

section = 2;
ps = 1; % with quarterwave phase shift (DFB)
% ps = 0; % without quarterwave phase shift (DBR)

for ii = 1:length(lambda)
    T0 = eye(2);
    for jj = 1:section
        if jj<=section/2
            kappa = kappa0;
        else
            if ps ==1
                kappa = -kappa0;
            else
                kappa = kappa0;

    end
7
end
end
end
end
% Hamming (Apodized)
\kappa = \kappa \times (0.54 - 0.46 \times \cos(2 \pi j j / \text{section}));

% Gaussian
\m = 4;
\% z = jj * L / \text{section};
\% FWHM = 0.3 * L;
% \kappa = \kappa \times \exp(-\log(2) \times (2 \times ((z - L / 2) / \text{FWHM})^{2 * \m}));

\sigma = 2 \times \text{neff} \times \pi / \lambda(ii) - \pi / \lambda(df);
\gamma = \sqrt{\sigma^2 - (\text{abs}(\kappa))^2};

\mathbf{T} = \text{zeros}(2, 2);
\mathbf{dL} = \mathbf{L} / \text{section};
\mathbf{T}(1, 1) = \cosh(j \times \gamma \times \mathbf{dL}) - \sigma / \gamma \times \sinh(j \times \gamma \times \mathbf{dL});
\mathbf{T}(1, 2) = -\text{conj} \times \kappa / \gamma \times \sinh(j \times \gamma \times \mathbf{dL});
\mathbf{T}(2, 1) = \kappa / \gamma \times \sinh(j \times \gamma \times \mathbf{dL});
\mathbf{T}(2, 2) = \cosh(j \times \gamma \times \mathbf{dL}) + \sigma / \gamma \times \sinh(j \times \gamma \times \mathbf{dL});

\mathbf{T0} = \mathbf{T} \times \mathbf{T0};
end
r(ii) = \mathbf{T0}(2, 1) / \mathbf{T0}(2, 2);
t(ii) = \text{det} \times \mathbf{T0} / \mathbf{T0}(2, 2);
end
% max(abs(r).^2+abs(t).^2)
r = 20 \times \text{log10} \times (\text{abs}(r));
t = 20 \times \text{log10} \times (\text{abs}(t));
\lambda = \lambda';
r = r';
t = t';
\dBRef(i) = \text{max}(r);
\dBTrans(i) = \text{min}(t);
\text{strength}(i) = \kappa \times \mathbf{L};
i = i + 1;

\text{figure}1 = \text{figure}(\text{'Color', [1 1 1]}); \% create a figure with white background
\text{axes}1 = \text{axes}(\text{'Parent', figure1},
\quad \text{'FontWeight', 'bold',}
\quad \text{'FontSize', 24}); \% adjust font size for the axis
Appendix IV List of Publications

**Journal Articles**


*contributed equally

**Conference Presentations**


and Electro-Optics, OSA Technical Digest (online) (Optical Society of America, 2018), paper SM3L.1.