Characterization of Photonic Crystal Based Silicon-on-Insulator Optical Circuits Fabricated by a CMOS Foundry

by

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B.A.Sc. Queen’s University, 2009

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(Physics)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

October 2011
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Abstract

Prototype silicon photonic circuits in a silicon-on-insulator (SOI) wafer fabricated using a CMOS-based single layer process, are thoroughly characterized. Thousands of devices were fabricated on a single 200 mm diameter wafer using deep UV lithography at the IMEC silicon photonics foundry. The devices studied integrate three key elements: i) input/output grating couplers, ii) waveguides, and iii) microcavities. The photonic crystal cavities are symmetrically coupled to input and output single mode channel waveguides, which couple light into tapered waveguides that are terminated by two-dimensional photonic crystal gratings couplers.

The grating coupler efficiencies and bandwidths are studied independently from the other device components, both experimentally and by simulations, using free-space optics. At a fixed angle of incidence, light over a bandwidth of approximately 14 nm (TE) and 30 nm (TM) is coupled from grating to grating, in both experiments and simulations. The centre frequency of this coupling spectrum is tuned by varying the angle of incidence on the grating, by coating the grating with photoresist, and by varying the size of the holes that form the grating.

The maximum net single-grating coupling efficiencies are measured to be 15% (26%) for TE (TM) coupling. Taking into account the limited aperture of the collection optics, and aberrations of the input coupling lenses, these measured net efficiencies are reasonably consistent with simulated true efficiencies of 21%(49%) found using Lumerical FDTD Solutions™ and MODE Solutions™ commercial software.

Resonant transmission measurements from free space, via an input grating, through the complete integrated photonic circuit, including the photonic crystal microcavity, and off-chip via an output grating are measured for a number of different cavities. The transmission of light from the end of one tapered waveguide, through the cavity, to the end of the other tapered waveguide is found to be ∼ 10%. The maximum microcavity quality factor measured is ∼ 5000.

This work demonstrates that fully integrated photonic circuits can be successfully fab-
icated using IMEC’s CMOS foundry service. It further shows that useful overall coupling efficiencies can be realized using free space optics, which will be useful for probing such circuits when they are placed inside optical cryostats.
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Acknowledgements

I would like to sincerely thank Dr. Jeff Young for his all of his patience and time throughout the duration of this research. His guidance and knowledge has made this a tremendously valuable learning experience.

I would like to thank fellow students Charles Foell, Hamed Mirsadeghi, Jonathan Massey-Allard and Stephanie Flynn for creating a friendly and supportive work environment. I would also like to thank Simon Dickreuter, with whom I did initial device characterization work. And many thanks to Dr. Georg Rieger, whose help was essential in designing and constructing optical experiments, and to Dr. Mario Beaudoin and Dr. Alina Kulpa for their help in the cleanroom.

Finally, I would like to thank Dan Deptuck and CMC Microsystems, who assisted in the fabrication of the devices studied in this thesis, which was performed in the frame of ePIXfab set-up by IMEC vzw and CEA-LETI.
Chapter 1

Introduction

1.1 Motivation and Objectives

The advent of the transistor in the late 1940’s marked the beginning of the information age. Transistors became the building blocks of sophisticated semiconductor based electrical integrated circuits, performing information processing tasks. From 1958 to 1965, the number of components on a chip roughly doubled each year as rapid advancements were made towards miniaturizing electronic circuits. This trend, known as Moore’s Law, continues to describe the evolution of current technologies [29]. The invention of the laser in 1960 revolutionized the information transmission infrastructure. Copper wires connecting microelectronic chips were replaced by optical fibres that could efficiently transfer light, or photons, causing the global expansion of information networks.

To a large extent, data processing and transmission tasks are still performed in separate modules in commercial information schemes. Glass fibres transport optically encoded signals between optical components such as modulators and filters and eventually to photodetectors that convert the light to electrical current [7]. Information processing of the electrical signals, like switching and routing, is then performed by CMOS microelectronic chips.

Over the past decade, progress have been made towards integrating multiple optical components compactly on a small chip. Elements such as waveguides, resonators, wavelength-division multiplexers and input/output ports are etched in two dimensional wafers to form
planar “photonic circuits”. One ongoing objective is to work within this framework of “integrated optics” to replace racks of discrete optical components with miniature optical chips that still output electrical signals to be processed using CMOS electronics. The ultimate goal is to go one step further and design photonic circuit elements that can perform switching and routing tasks to eliminate conversions between optical and electrical signals.

The central role silicon plays in the semiconductor industry, as the platform of information processing, makes it an attractive candidate for photonic device integration over other common materials like GaAs, InP and LiNbO$_3$ [26], [35]. Not only can the advanced fabrication processes developed for silicon electronic circuits be applied in the fabrication of silicon photonic devices, the devices can be integrated with electronic components to form efficient, high-speed optoelectronic circuits [35]. Silicon photonic devices are increasingly attracting the attention of the photonics community as advances in fabrication technologies are making it possible to successfully realize a wide range of devices in silicon at relatively low cost. Over the past two years, two international silicon photonic foundries have opened, offering industrial-scale fabrication of integrated electronic and photonic elements on large area silicon wafers.

Waveguides are fundamental components of most photonic devices as they transport light to and from different components on a chip. Ridge waveguides (illustrated figure 1.1), are standard to most photonic circuits. These waveguides are commonly made in a slab sitting on a substrate with a lower index of refraction. Due to the decrease in the index of refraction at the ridge interfaces, waveguides modes are confined to the slab region below the ridge and decay outside of the slab. This confinement is greatest for large index contrasts. A ridge waveguide can be partially etched with the ridge sitting on a pedestal (as in figure 1.1a) or fully-etched (as in figure 1.1b). The latter are also called photonic wires. Waveguides can be designed to support multiple modes or a single mode for a given polarization. Silicon-on-insulator (SOI) wafers from the semiconductor industry provide a good base for photonic devices as the top layer of silicon ($n = 3.47$ near 1550nm) sits on a low index SiO$_2$ substrate ($n = 1.46$ near 1550nm) [19]. Ridge waveguides are commonly etched into the silicon layer of the SOI using electron beam lithography [26] and more recently deep UV lithography [8].
Photonic wires in SOI propagate light with loss as low as 0.24dB/mm [9], where most of the loss is attributed to light scattering off rough surfaces. They therefore offer a means of effectively interconnecting many micron-scale photonic devices on centimetre scale chips.

Filters and switches are examples of photonic devices commonly studied for integrated optoelectronic telecommunication link applications. A structure that acts as a filter is a ring resonator coupled to two waveguides, as illustrated in figure 1.2. The waveguides are ridge waveguides and the ring is a ridge waveguide with a radius of curvature chosen to minimize loss and to provide the desired free spectral range. Light will only couple from Waveguide A to Waveguide B at the resonance frequencies of the ring. This occurs when light travelling one lap in the ring covers a distance that is an integer number of wavelengths causing there...
to be constructive interference with the in-coupled light. Like other optical resonators, this interference condition allows high intensity light to be stored in ring waveguide. A fraction of the light in the ring will couple to Waveguide B and leave the system. This scheme acts as a compact, integrable frequency filter where only light at the resonance frequencies of the ring passes to Waveguide B while the rest of the light is transmitted past the ring in Waveguide A.

This structure can also be used as a switch when integrated with active components, such as heaters or pn junctions. Active control of the index of refraction of a ring resonator provides a means of varying its resonance frequencies. The refractive index can be modified by injecting free-carriers into the ring waveguide either electronically, by incorporating a p-i-n diode into the waveguide, or by optical excitation above the silicon band gap [26]. For a given input optical signal of specified wavelength, the device can be tuned to an ON state, when the index of refraction allows the resonant transmission of the signal wavelength, and to an OFF state otherwise.

Light must be eventually coupled from single mode optical fibres to and from these on-chip waveguides. Conventional optical fibres have mode diameters of approximately 10µm, while waveguides in photonic circuits are generally much smaller with widths and thicknesses on the order of hundreds of nanometers. The mismatches in the mode profiles and propagation wavevectors (or effective indexes) of waveguide and fiber modes make coupling a challenging task. Directly butt-coupling the fiber to the facet of a typical ridge waveguide results in insignificant coupling. A popular coupling technique is the inverse taper method [24], [2]. The width of the waveguide is tapered from its operational width inside the circuit, to a nanometer-sized width at the edge of the chip, where the tip is aligned with the center of the optical fibre, as is illustrated in figure 1.3a. Light is increasingly delocalized from the waveguide core along the length of the tapered section due to the subwavelength width of the taper. The resulting waveguide mode at the fibre has a mode profile and effective index similar to those of the fibre mode. Light can also be coupled from a fiber into a waveguide using this method in reverse. The transmission efficiency for a fiber/SOI waveguide/fiber system (with tapered waveguides at the fiber interfaces) was found to be 12% with a 42µm
taper length [2]. While the coupling efficiency is reasonably high, the inverse taper is very delicate and difficult to reproducibly fabricate and package. In addition, there is little flexibility in the arrangement of multiple devices on a chip.

An alternative approach, that is studied in detail in this thesis, is grating coupling. Gratings are commonly made by etching periodic 1D or 2D patterns in a dielectric slab. In this coupling scheme, a fibre is brought to the surface of a grating and is tilted at a small angle (typically around 10°) from the vertical as is illustrated in figure 1.3b. The periodic modulation in the dielectric constant of the slab causes incident light to diffract and excite modes in the grating region when phase matching and polarization requirements are met. The grating modes excite modes of an adjacent waveguide that has a width that is slightly larger than the diameter of the fiber mode (> 10µm). The waveguides are tapered so that their width slowly decreases along their axis to the size of the photonic wire, for adiabatic mode transformation. The taper must be an appropriate length so that there is little reflection in the waveguide due to mismatching of the mode profiles and effective indices along the propagation axis. The tapered waveguide designs are optimized to be compact while maintaining high impedance matching. To couple light out of a waveguide mode in a photonic wire, the same taper and grating combination can be used in reverse. Coupling efficiencies as high as 43% with a 3dB bandwidth of 60nm have been reported [17].

There are numerous different types of waveguide and optical resonators systems with input/output couplers that are being optimized to achieve high performance with ultrasmall footprints. Applications of photonic devices are not limited to telecommunications, they can also be used in sensing and quantum information processing. As previously mentioned, one advantage of working with silicon-on-insulator (SOI) based devices is that they can be fabricated using techniques developed in the semiconductor industry. In the past decade, it has become possible to move away from electron beam lithography techniques and towards high density, low cost production using existing CMOS fabrication technologies. Silicon photonics foundry services, such as those run by the Interuniversity Microelectronic Center (IMEC) in Leuven, Belgium and the Optoelectronics Systems Integration in Silicon (OpSIS) project in Seattle, USA, allow researchers to share production costs as multiple projects are
Figure 1.3: Fiber/waveguide coupling schemes. a) Inverse taper: A waveguide is tapered down to nanometer-sized width so that waveguide modes supported near the fibre interface are delocalized from the waveguide core resulting in a mode profile and effective index suitable for coupling to a fibre mode b) Grating coupler: Periodic modulations in the slab causes light from a fibre at an angle $\theta$ to the vertical to diffract and excite modes in a wide tapered waveguide that shrinks to a single mode waveguide. The arrow shows the direction of propagation for in-coupling. The spot near the end of the waveguide is meant to show the tight confinement of light after the tapered waveguide.
distributed on the same wafers. These foundries use deep UV lithography to etch a pattern in the top silicon layer of an SOI wafer [8], as is done in the CMOS industry. This fabrication technique makes it possible to mass produce compact devices at low cost, a feat that is not feasible using most conventional “one-of” fabrication techniques such as electron-beam lithography. Not only is this a step towards realizing future wide scale production of devices for end users, this is ideal for prototyping new devices as several thousand nearly identical devices can be realized in a single run. As each etching step adds a level of complexity and significantly increases the production cost, one challenge is to design photonic circuits, with many different functional elements in a single processing step, sometimes referred to as a “single layer process”.

The work described in this thesis involves thoroughly characterizing prototype, passive, one-step-etch silicon photonic circuits made at the IMEC foundry. Each circuit, which is replicated thousands of times on the 200mm diameter wafer, incorporates three key elements: i) input/output grating couplers ii) single-mode waveguides and, iii) wavelength scale microcavities. These three elements can be configured for a wide range of applications where optical signals are processed then sent off the chip. Although many variations of these individual elements have been developed and characterized by us and others, few examples of complete circuits, like these, exist.

The devices studied in this thesis have grating couplers that diffract light into and out of waveguides that are symmetrically located on either side of a photonic crystal circuit that includes waveguides and a microcavity, as is shown in figure 1.4. The flow of light in these devices is illustrated in figure 1.4. Note that the schematic diagram in figure 1.4 is not to scale: the actual devices have the grating couplers separated by $\sim 600\mu$m, and the photonic crystal cavity region is $\sim 10 \mu$m in extent. When light is coupled into the system at the resonance frequency of the cavity, high intensity light is captured in the cavity and is transmitted to the output waveguide and is eventually diffracted off the chip to a detector. Light is not transmitted off resonance. This ability to transfer photons to and from the cavity to free-space makes these devices suitable for numerous linear and nonlinear applications. The devices are currently being integrated with quantum dots for single photon, non-classical
Figure 1.4: Schematic of the flow of light in a device studied in this thesis (not to scale). Light incident on a grating coupler excites waveguide modes in a tapered waveguide which shrinks to a single mode waveguide designed to couple light to a photonic crystal waveguide. Resonant light couples to and from a photonic crystal microcavity mode and is transmitted to the output tapered waveguide terminated by grating coupler where light is diffracted off the chip. Solid arrows show the direction of light propagation (reflections are not shown).

light source applications by other researchers in our laboratory. The basic idea is to excite a semiconductor quantum dot sitting at the center of the cavity. The dot can absorb a photon and later emit it at a different frequency so that the dot can be excited away from the cavity resonance frequency but emit a photon that resonantly couples to the cavity. This cavity coupled photon can then be collected after travelling out of the system via a grating coupler.

While ring resonators are one type of integrable microcavity, their size is limited by radiation loss as the radius of curvature decreases, and the free spectral range increases. Photonic crystals offer a route to miniaturize microresonators to a wavelength scale, in some cases with effectively infinite free spectral range. They also offer a platform for ultracompact photonic circuits in which photonic crystal waveguides connect elements, such as microresonators, for optical processing tasks. A photonic crystal is a periodic arrangement of dielectric materials. A two-dimensional crystal may be fabricated by etching a periodic array of holes in the top silicon layer of an SOI wafer. A fundamental property of photonic crystals that is exploited in many applications is the photonic band gap. The band gap is a range of frequencies over which light is prohibited from propagating in the crystal. The omission of
one or more holes in a 2D photonic crystal creates an optical microcavity where light at certain frequencies is trapped in a very small volume, for many optical cycles, much like a ring resonator, but much smaller. There are many existing photonic crystal microcavity designs, including the air-slot cavity [38], the double heterostructure cavity [34] and the L3 cavity encountered in this thesis. An L3 cavity exists in a 2D photonic crystal when three adjacent holes are omitted as is illustrated in figure 1.5a [1]. A whole row of holes can also be omitted to create a photonic crystal waveguide, as illustrated in 1.5b. Extensive work has been done to optimize the resonant properties of isolated photonic crystal cavities and cavities coupled to photonic crystal waveguides. Many different geometries can be used to couple photonic crystal microcavities to waveguides. Much like the ring resonator systems described above, the microcavities can be side-coupled to waveguides, as illustrated in figure 1.6a. Light travelling at the cavity resonance frequency in Waveguide A couples to the cavity and in turn couples to Waveguide B while off-resonant light does not excite the cavity and light is not transferred to Waveguide B. The devices studied in this thesis include photonic crystal microcavities that are coupled to photonic crystal waveguides by leaving two holes on either side of the photonic crystal while removing the rest of the row of holes as shown in figure 1.6b. The photonic crystal waveguides are coupled to single mode ridge waveguides which in turn couple light to tapered waveguides that are terminated by grating couplers.

The gratings studied in this thesis are rectangular lattices of holes in the top silicon layer of the SOI wafer and are designed as input/output ports as suggested by a 2006
Figure 1.6: Examples of photonic crystal cavity and waveguide coupling geometries. a) Schematic of an L3 cavity side coupled to two waveguides for a filtering scheme like that described for ring resonators (see figure 1.2) b) Schematic of waveguides butt coupled to a cavity. The devices in this thesis have this coupling geometry.

patent [31]. While many different types of grating couplers have been studied, the majority of grating coupler literature is based on shallow etched gratings, where the etch extends only partly through the slab. Grating coupling efficiencies of 37% have been reported for shallow-etch gratings [37]. Similar structures with reflectors below the slab yield even higher coupling efficiencies. Shallow-etch gratings structures can be made using CMOS fabrication techniques, however, an additional lithography and etching step is required to make fully-etched photonic wires or photonic crystals on the same wafer. It is therefore desirable to develop deep-etched gratings from a cost-of-fabrication perspective, without sacrificing, or perhaps even enhancing performance.

In 2009, Halir et al proposed a design of a grating coupler with sub-wavelength sized rectangles fully-etched in the silicon layer of an SOI wafer, with a predicted a coupling efficiency of 50% [16]. A similar design was later fabricated by Halir and was experimentally found to have 43% coupling efficiency with a 3dB bandwidth of 60nm. Large bandwidths are characteristic of most fully-etched gratings and make it possible to operate the gratings with flexibility in frequency and coupling angles. Fully-etched grating designs for efficient mode coupling for specific polarizations have also been reported in [27],[10], [11] and [3]. Grating designs include a 2D photonic crystal grating like the one studied in this thesis [10], a 1D chirped grating where grooves in the silicon are unevenly spaced for optimized fiber mode matching [3] and a grating that substitutes 1D conventional groove regions by fully-etched
photonic crystal holes [27].

Chen et al recently reported a design for a fully-etched, polarization independent grating coupler with a theoretical coupling efficiency above 60% [11]. This is the only publication found to report on grating coupling, with a full-etched design, for different polarizations. To the author’s knowledge, there are no current publications reporting experimental multi-polarization grating coupling results for fully-etched gratings.

The objective of this thesis is to measure the optical properties of numerous foundry-made photonic circuits and circuit elements under a variety of conditions to examine their performance and assess their suitability for future applications. An optical set-up was designed and implemented to measure the resonant cavity transmission of light through devices where light is coupled into the chip via a grating coupler using two different excitation schemes, fibre and free-space coupling, and light is diffracted off the chip into free-space via a second grating coupler, and is monitored using a detector. Fibre excitation involves positioning a single mode fibre directly above a grating whereas in free-space coupling, lenses are used to collimate light from a single mode fibre, and then focus it onto a grating.

One advantage of direct fibre excitation is that the mode diameter at the fiber tip is reliably close to 10µm. Another advantage is that fibres can be easily incorporated in automated wafer testing apparatuses for both input and output coupling. One major disadvantage is that fiber coupling becomes extremely challenging when dealing with samples in solution or in cryostats, as is common in our research environment. In such cases it is much more convenient to use free space excitation and collection optics, and one of the important questions addressed in this thesis, is how efficient the coupling can be with free-space optics.

1.2 Thesis Layout

In the first chapter, an heuristic approach is taken to describe the physics governing electromagnetic fields in a slab waveguide geometry. Following a discussion of the dispersion properties of electromagnetic modes bound to 2D dielectric slabs, the principles behind shallow-etch, perturbative, or “weak” grating couplers are discussed. Two different ways of
describing the characteristics of “strong” grating coupling are offered. Photonic band gap devices such as microcavities are then discussed and the chapter finishes with a description of the numerical methods used to solve for “exact” electromagnetic fields in our samples.

The devices studied in the rest of this thesis are described in detail in chapter 3. The design of the devices are described as well as the fabrication procedure and final product. An outline of the post-fabrication treatments used to enhance the performance of the devices concludes chapter 3.

The focus of chapter 4 is on simulations done using commercial software to predict and attempt to explain the measured optical properties of the grating couplers. The transmission set-up used to make the measurements reported in this thesis is described in chapter 5. The grating characterization results are reported in chapter 6. The chapter begins with a description of the measurement procedure followed to take grating coupling efficiency measurement. The characterization results are presented and the chapter finishes with a comparison of experimental and simulation results to those in the literature. Resonant cavity transmission results are then presented in 7.

The concluding chapter of this thesis summarizes the results presented in chapter 6. Recommendations are made for a transmission set-up design for higher quality results and easier manipulation.
Chapter 2

Theory

In this chapter, the physics behind the functionality of devices encountered in this thesis is described. A significant portion of the experimental characterization of the microcavity/waveguide/grating coupler devices (illustrated in figure 1.4) is devoted to measuring the optical properties of the grating couplers. To a large extent, this is done by coupling light into the silicon slab via one grating coupler, then diffracting light out of the slab via a second grating coupler. This grating to grating experiment is illustrated in figures 2.1a and 2.1b for forwards and backwards coupling geometries respectively. Arrows indicate the direction of propagation of light. In the experimental procedure, the light source is either directly from a fibre in close proximity to the grating, or the fibre output is imaged onto the grating using free space optical elements (as was discussed above in chapter 1). The incident light is shown as a circular beam in figure 2.1. The angle of the incidence, $\theta$, is controlled and a polarizer is used to set the input polarization. The incident light is said to be S-polarized when the electric field is polarized parallel to the slab surface and is said to be P-polarized when the field is polarized in a plane normal to the surface, as illustrated in figure 2.2. For the measurements taken, forward coupling geometries (as in figure 2.1a) were used for S-polarized excitation and backwards coupling geometries (as in figure 2.1b) were used for P-polarized excitation. The collection optics, which directs light diffracted from the output grating to a detector, are centered at an angle $\theta$ from the vertical and a second polarizer is placed in front of the detector. This is summarized in figure 2.3 where double-headed arrows show the
Figure 2.1: Schematics of light flow in grating to grating transmission experiments. Light incident on a grating at an angle $\theta$ (cylindrical beam) excites quasi-bound grating modes which in turn excite bound slab modes that propagate towards a second grating where light is diffracted off the chip. Arrows show the direction of light flow for a) forward coupling and b) backwards coupling geometries.
Figure 2.2: Light incident on a surface is $S$ polarized when the electric field is parallel to the surface and $P$ polarized when magnetic field is parallel to the surface.

Figure 2.3: Schematic of coupling geometries for light incident a) $S$ polarized and b) $P$ polarized. Black arrows indicate the direction of light propagation into and out of the gratings. Red double sided arrows indicate the direction of the input and collection polarizers.

For each measurement, the frequency of the incident light from a narrow linewidth (30pm) tuneable diode laser is swept through a range of frequencies and the amount of power diffracted from the output grating is measured by a detector.

In this chapter, qualitative explanations of grating coupling are provided to provide a basis for interpreting the experimental and numerical results presented in later chapters. In section 2.1, Maxwell’s equations are introduced and used to find an analytic expression for the dispersion of bound modes supported by a dielectric slab on a substrate. A 1D weak grating structure is then studied in section 2.2.1. In section 2.3, band structure theory is used to help explain the physics of 1D strong grating structures and this theory is extended to 2D strong grating in section 2.3.2. Photonic band gap based devices such as microcavities and waveguides are visited in section 2.4. Numerical methods used later for quantitative comparisons with experimental results are discussed in section 2.5.
2.1 Dielectric Slab Dispersion

To develop a theoretical understanding of the physics describing grating couplers, the harmonic electromagnetic field solutions of the macroscopic Maxwell’s equations,

\[ \nabla \cdot \mathbf{D}(\mathbf{r}) = \nabla \cdot \mathbf{H}(\mathbf{r}) = 0 \]  
\[ \nabla \times \mathbf{E}(\mathbf{r}) - \frac{i\omega}{c} \mathbf{H}(\mathbf{r}) = 0 \]  
\[ \nabla \times \mathbf{H}(\mathbf{r}) + \frac{i\omega}{c} \mathbf{D}(\mathbf{r}) = 0 \]

are sought, where the electric and magnetic fields are expressed as,

\[ \mathbf{E}(\mathbf{r}, t) = \text{Re}(\mathbf{E}(\mathbf{r}, \omega)e^{-i\omega t}) \]  
\[ \mathbf{H}(\mathbf{r}, t) = \text{Re}(\mathbf{H}(\mathbf{r}, \omega)e^{-i\omega t}) \]

The frequency dependence of \( \mathbf{E}(\mathbf{r}) \) and \( \mathbf{H}(\mathbf{r}) \) is suppressed to simplify notation, as will done throughout this thesis. The displacement field, \( \mathbf{D}(\mathbf{r}) \), may be written in terms of the electric field and the polarization, \( \mathbf{P}(\mathbf{r}) \):

\[ \mathbf{D}(\mathbf{r}) = \mathbf{E}(\mathbf{r}) + 4\pi \mathbf{P}(\mathbf{r}) \]

An electric field causes the electrons in a medium to move which generates a dipole moment density, \( \mathbf{P}(\mathbf{r}) \), where in the linear response regime,

\[ \mathbf{P}(\mathbf{r}) = \chi(\mathbf{r})\mathbf{E}(\mathbf{r}) \]

Here \( \chi(\mathbf{r}) \) is the linear susceptibility. When (2.7) applies, \( \mathbf{D}(\mathbf{r}) \) may be written as

\[ \mathbf{D}(\mathbf{r}) = (1 + 4\pi \chi(\mathbf{r}))\mathbf{E}(\mathbf{r}) = \epsilon(\mathbf{r})\mathbf{E}(\mathbf{r}) \]

where \( \epsilon(\mathbf{r}) \) is the linear dielectric constant, which can be a function of position.
The challenge is to find $E(r)$ and $H(r)$ fields that solve (2.3) in nontrivial dielectric landscapes described by $\epsilon(r)$. Decoupling the last two equations and applying (2.8) reduces to solving an eigenvalue problem for $H(r)$ from which $E(r)$ can be readily found. This eigenvalue problem, may be written as:

\[ \nabla \times \left( \frac{1}{\epsilon(r)} \nabla \times H(r) \right) = \left( \frac{\omega}{c} \right)^2 H(r) \]  

(2.9)

\[ \Theta H(r) = \left( \frac{\omega}{c} \right)^2 H(r) \]  

(2.10)

where $H$ is the eigenfunction, $(\omega/c)^2$ is the eigenvalue and $\Theta$ is an Hermitian operator. This can be compared to the energy eigenvalue problem encountered in quantum mechanics that arises from Schrodinger’s equation with eigenfunction $\Psi$ and eigenvalues $E$. While these are distinct eigenvalue problems that describe different physics, their solutions have similar forms making it useful to draw parallels between the behaviour of electromagnetic and quantum mechanical systems.

Analogous to quantum mechanics, it can be shown that due to the Hermitian nature of the operator, one can apply the variational method to investigate the relative energy of the harmonics modes. It can be shown that each orthogonal harmonic mode of a dielectric system will minimize the electromagnetic energy functional [20]:

\[ U_f = \int d^3r H^*(r) \Theta H(r) \]

(2.11)

\[ = \frac{\int d^3r H^*(r) \Theta H(r)}{\int d^3r H^*(r) H(r)} \]

Insight into how the field pattern of a mode is related the mode energy (or frequency) may be drawn from inspecting the energy functional evaluated for the harmonic modes. After some manipulation, the functional can be written in terms of the electric field:

\[ U_f = \frac{\int d^3r |\nabla \times E(r)|^2}{\int d^3r \epsilon(r) |E(r)|^2} \]  

(2.12)

One can interpret from (2.12) that field distributions concentrated in high dielectric regions have relatively low energy. High dielectric constant regions are analogous to regions of low potential energy in quantum mechanics problems.
A dielectric slab is a simple structure that may be solved analytically and is directly relevant to this thesis. Of interest are the bound electromagnetic modes supported by a uniform dielectric slab extending to infinity in the \( x - y \) plane with air above and a dielectric substrate below, as shown in figure 2.4.

![Figure 2.4: Illustration of an SOI dielectric slab structure. A 220nm thick layer of silicon sits on an SiO\(_2\) substrate.](image)

Because the dielectric constant of every layer has translational invariance in the \( x - y \) plane, \( \epsilon(\mathbf{r}) = \epsilon(\mathbf{r} + \mathbf{d}_{xy}) \), the translation operator \( T_d \), which acts on a function of \( \mathbf{r} \) by taking \( \mathbf{r} \) to \( \mathbf{r} + \mathbf{d}_{xy} \), commutes with \( \Theta \):

\[
T_d \left( \Theta(\mathbf{r}) \mathbf{H}(\mathbf{r}) \right) = T_d \left( \frac{\mathbf{z}}{\epsilon} \right)^2 \mathbf{H}(\mathbf{r}) = \left( \frac{\mathbf{z}}{\epsilon} \right)^2 \mathbf{H}(\mathbf{r} + \mathbf{d}_{xy}) = \Theta(\mathbf{r}) T_d \mathbf{H}(\mathbf{r}) \tag{2.13}
\]

Waves propagating without decay in the \( x - y \) plane and modulated in \( z \) are eigenfunctions for the simple eigenvalue problem associated with \( T_d \) (for vector \( \rho \) in the \( x - y \) plane),

\[
T_d e^{i\beta \rho} f(z) = e^{i\beta \cdot (\mathbf{r} + \mathbf{d}_{xy})} f(z) = e^{i\beta \cdot \mathbf{d}_{xy}} e^{i\beta \rho} f(z) \tag{2.14}
\]

Since \([T_d, \Theta] = 0\), the transverse mode solutions may be therefore labelled by the in-plane
wavevector $\beta$,

$$H_\beta(r) = H_0 e^{i\beta \rho} f(z)$$  \hspace{1cm} (2.15)

To solve the eigenvalue equation in (2.9), it is easiest to consider the electromagnetic field in each material separately where $\epsilon(r)$ is a constant, $\epsilon_i$ ($i$ indicating the three materials). This reduces (2.9) to

$$\frac{1}{\epsilon_i} \nabla \times \nabla \times H_\beta(r) = \left(\frac{\omega}{c}\right)^2 H_\beta(r)$$  \hspace{1cm} (2.16)

where $\nabla^2$ is the vector Laplacian. Applying the identity $\nabla \times \nabla \times H = \nabla (\nabla \cdot H) - \nabla^2 H$ and setting $\nabla \cdot H = 0$, (2.16) simplifies to

$$\nabla^2 H_\beta(r) = -\left(\frac{\omega}{c}\right)^2 \epsilon_i H_\beta(r)$$  \hspace{1cm} (2.17)

A mode travelling in the $\hat{x}$ direction is called transverse electric (TE) when the electric field is polarized parallel to the slab plane in the $\hat{y}$ direction (and magnetic field in $\hat{z}$) and transverse magnetic (TM) when the magnetic field is polarized parallel to the slab plane (and electric field in $\hat{z}$), as indicated in figure 2.5. Solving (2.17) for the TE and TM modes (which are the only two independent polarizations supported by this geometry) by applying the appropriate boundary conditions, it is possible to generate a dispersion diagram for the structure that conveys what the energy (or equivalently eigenvalue $(\omega/c)^2$) is for a mode with in-plane wavevector $\beta$. The dispersion diagram for a structure with $n_0 = 1$ (air), $n_{sub} = 1.444$ (SiO$_2$) and a slab thickness $t = 220$nm with $n_1 = 3.4784$ (Si) is shown in figure 2.6. These refractive indexes are valid near 1550nm. The modal behaviour in each of the three labelled regions of interest can be explained upon putting $H_{\beta,n}^{TE} = H_0 \beta e^{i\beta x} f(z)$ (found from $E_{\beta,n}^{TE} = E_0 e^{i\beta x} f(z)\hat{y}$) and $H_{\beta,n}^{TM} = H_0 e^{i\beta x} f(z)\hat{y}$ into (2.17) where $n$ indicates the mode order which will be discussed below. In both cases (2.17) reduces to

$$\frac{\partial^2 f}{\partial z^2} = \left(\beta^2 - \frac{\omega^2}{c^2} \epsilon_i\right) f$$  \hspace{1cm} (2.18)

Region I in figure 2.6 lies above the air light line ($\omega = c/\beta$) (the dash-dot line) and the
substrate light line \((\omega = c\beta/n_{sub})\). In both air and in the substrate, the solutions to (2.18) are plane waves \(f(z) \propto e^{ikz}\) where the superscript \(i\) is again used to indicate the different media. This results in a continuum of *leaky* unbound modes free to propagate in the slab, substrate and air. In Region II, \(f(z)\) is a decaying exponential in air and remains oscillatory in the substrate. These are also unbound modes as they are free to propagate in the substrate. Below the air and substrate light lines, in Region III, the modes are concentrated in the slab and decay outside the slab. Applying TE and TM boundary conditions at the air-slab interface, multiple modes may be found for the same \(\beta\) resulting in distinct transverse modes labelled by their mode order \(n\) (solid lines, TE red, TM blue). The conditions that must be met for TE and TM bound modes are (2.19) and (2.20) respectively \[30]\,

\[2v\sqrt{1-b} = m\pi + \tan^{-1}\left(\frac{n_0^2}{n_{sub}^2}\sqrt{\frac{b}{1-b}}\right) + \tan^{-1}\left(\frac{n_1^2}{n_0^2}\sqrt{\frac{b+\gamma}{1-b}}\right)\] (2.19)

\[2v\sqrt{1-b} = m\pi + \tan^{-1}\left(\sqrt{\frac{b}{1-b}}\right) + \tan^{-1}\left(\sqrt{\frac{b+\gamma}{1-b}}\right)\] (2.20)
Figure 2.6: Dispersion diagram for the dielectric slab structure in figure 2.4. Mode frequencies are plotted against their in-plane wavevectors, $\beta$. Four regions of interest are labelled (I, II, III, IV). Region I lies above the air light line (dashed-dot line) and contains a continuum of radiation modes. Region II lies above the substrate light line (solid straight line) and contains a continuum of unbound modes that are radiative in the substrate. Discretely separated TE (red) and TM (blue) bound modes exist in Region III (solid curved lines) while no modes exist below the bulk silicon light line (dashed line) in Region IV.

where

$$b = \frac{n_1^2 - n_{sub}^2}{n_1^2 - n_{sub}^2}$$

$$v = \sqrt{\frac{\omega^2}{c^2} \left(\frac{1}{2}\right)^2 \left(n_1^2 - n_{sub}^2\right)}$$

$$\gamma = \frac{n_{sub}^2 - n_1^2}{n_1^2 - n_{sub}^2}$$

These bound modes propagate in the $\hat{x}$ direction with $\beta = n_e \omega / c$ where $n_e$ is frequency dependent and is called the effective index of the mode. It is important to note that it is the different boundary conditions for TE and TM modes give rise to the a separate set of bands for each polarization. An electric field parallel to an interface must be continuous across the interface, whereas an electric field perpendicular must satisfy $\epsilon_1 E_{11} = \epsilon_2 E_{12}$.

The light-line of the bulk slab material (the dashed line in figure 2.6) has a slope equal to the speed of light in that material ($c/n_1$). No modes exist in Region IV because the
total wavevector may not exceed $\omega/n_1$. The bands in Region III are cut-off at the substrate light-line for low $\beta$ and extend towards the bulk dielectric material light line for large $\beta$. The cut-off occurs because modes become unbound above the substrate light-line as was previously discussed. For large $\beta$, the bound modes decay more quickly outside the slab and become more confined to the slab causing the band to asymptotically follow the dispersion of a wave propagating in the bulk slab material.

A plane wave incident on the slab from air at an angle $\theta$ to the normal will have an in-plane wavevector $\beta = \omega/c \sin \theta$, which will always be above the air light-line. This wave will be phase-matched (the in-plane component of the wavevector must be continuous in all media) to refract in the slab, as it is a continuum mode. The phase-matching condition required for coupling to a bound mode cannot be met by a plane wave propagating in the top half space because the bound modes have $\beta > \omega/c$. To enable coupling from a plane wave in free space, to a bound slab mode, the symmetry of the system must be broken so that the constraint on the in-plane wavevector is relaxed.

2.2 Weak Grating Couplers

In this section, a weak grating extending to infinity is studied and grating coupling is described using an approximate field solution. These principles are then applied to describe grating coupling with a finite sized weak grating.

2.2.1 Weak Gratings with Infinite Extent

This section deals with structures containing a weak one dimensional grating etched in the slab structure, as is illustrated in figure 2.7. The groove depth in the slab is much smaller than the thickness of the slab. The texturing has a period $\Lambda$ and the structure extends infinitely in the $x-y$ plane.

To study the fields resulting from a plane wave propagating the $x-z$ plane incident on this structure from free-space, a weak perturbation approach is used [13]. For convenience, we shall begin by considering the electric field equation of motion (instead of the magnetic
field equation of motion (2.9)),

\[ \nabla \times \nabla \times \mathbf{E}(r) - \left( \frac{\omega}{c} \right)^2 \epsilon(r) \mathbf{E}(r) = 0 \] (2.25)

where \( \epsilon(r) = \epsilon(r + \Lambda \hat{x}) \). To isolate the effect of the grating in (2.25), \( \epsilon(r) \) may be rewritten as,

\[ \epsilon(r) = \epsilon_s(z) + 4\pi \Delta \chi_g(r) \] (2.26)

where \( \chi(r) = \chi_s(z) + \Delta \chi_g(r) \) and \( \epsilon_s(z) = 1 + 4\pi \chi_s(z) \). The untextured slab structure (in figure 2.4) is described by \( \epsilon_s(z) \), and the modification due to the weak grating structure in figure 2.7, is described by the electric susceptibility \( \Delta \chi_g(x, z) \). Expanding \( \epsilon(r) \) in (2.25) yields,

\[ \nabla \times \nabla \times \mathbf{E}(r) - \left( \frac{\omega}{c} \right)^2 \epsilon_s(z) \mathbf{E}(r) = 4\pi \left( \frac{\omega}{c} \right)^2 \Delta \chi_g(x, z) \mathbf{E}(r) \] (2.27)

When the right side of (2.27) is set to 0, the homogeneous solution of (2.27) that is consistent with plane wave excitation incident from the top half space, corresponds to the specularly reflected and transmitted plane waves above and below the structure, and the multiply reflected field internal to the layered region. This homogeneous solution has the field components in all layers varying with the same wavevector in the plane, \( \beta_{inc} \), and it lies in the continuum of modes the structure in figure 2.6, above the air light-line.
Using this approach, the polarization generated in the grating,

\[ \Delta P_g(r) = \Delta \chi_g(x, z) E(r), \quad (2.28) \]

becomes the driving term that determines the inhomogeneous contribution to the total field solution of (2.27). From (2.25), Bloch’s theorem implies that

\[ E(r) = \sum_j E_j(z) e^{i(\beta_{inc} + j \frac{2\pi}{\Lambda})x}. \quad (2.29) \]

Using (2.29) and the fact that the grating is periodic in the \( \hat{x} \) direction with period \( \Lambda \), the grating polarization can be written in terms of its Fourier components,

\[ \Delta P(r) = \sum_j P_j(z) e^{i(\beta_{inc} + \frac{2\pi}{\Lambda}j)x}. \quad (2.30) \]

Applying (2.28) and (2.30) to (2.27), the driving term in (2.27) becomes,

\[ 4\pi \left( \frac{\omega}{c} \right)^2 \sum_j P_j(z) e^{i(\beta_{inc} + \frac{2\pi}{\Lambda}j)x} \quad (2.31) \]

It is clear that the grating creates driving terms in (2.27) that excite the uniform slab equation of motion at a set of in-plane wavevectors \( \beta_{inc} + j \frac{2\pi}{\Lambda} \). For a weak grating, when this equation is solved self-consistently, and when one of the \( \beta_{inc} + j \frac{2\pi}{\Lambda} \) (usually \( j = +1 \)) corresponds to the wavevector of a bound mode solution of the uniform slab, the total field in the slab region will be dominated by the bound mode, while the renormalized reflection and transmission fields associated with the \( j = 0 \) term of course remain bounded by flux conservation. This is the so-called phase-matching condition for grating-assisted excitation of bound modes, in this weak perturbation limit.

The problem that describes the coupling of light out of a bound slab mode is identical, except that the homogeneous solution to (2.27) is a bound mode of the uniform slab, and when one of the \( \beta_{inc} + j \frac{2\pi}{\Lambda} \) (usually \( j = -1 \)) is above the air light-line (i.e. \( < \omega/c \)), a continuum mode is driven by the grating polarization, and light diffracts out of the bound
2.2.2 Finite Weak Grating Couplers

In practice, grating couplers have a finite length and are excited with localized beams, as is illustrated in figure 2.8.

Figure 2.8: Illustration of a 1D finite weak grating. An untextured dielectric slab surrounds a grating region with a series of shallow-etched grooves spanning a finite distance in x. This structure is also called a “shallow-etched grating coupler”. A focussed beam incident on the grating coupler is illustrated.

To understand the implications of this, it is easiest to consider the polarization induced in the grating, $\Delta P_g(r)$ (as in (2.30)), which drives the field components necessary for grating coupling. In the spatial Fourier domain, the Fourier transform of $\Delta P_g(r)$ is,

$$P_g(\beta, z) = \int_{-\infty}^{\infty} \sum_j P_j(z) e^{i(\beta + \frac{2m \pi}{\Lambda})} dx$$  \hspace{1cm} (2.32)

$$P_g(\beta, z) = \sum_j P_j(z) \delta(\beta - (\beta_{inc} + \frac{2m \pi}{\Lambda}))$$ \hspace{1cm} (2.33)

This is an infinite series of delta functions separated by $2\pi/\Lambda$ multiplied by factors, $P_j(z)$. However, for the structure illustrated in figure 2.8, $\Delta P_g(r)$ in (2.30) is truncated by the length of the grating. It will also be approximately modulated by a Gaussian in the $x - y$ plane for a Gaussian beam excitation. The finite-extent polarization, still in the weak grating limit, becomes

$$\Delta P^f(r) = \sum_j P_j e^{i(\beta_{inc} + 2m \pi/\Lambda)x} G(x) Rect(x/L)$$ \hspace{1cm} (2.34)
where \( G(x) \) is a Gaussian, \( \text{Rect}(x/L) = 1 \) when \(-L/2 < x < L/2\) and = 0 elsewhere and \( L \) is the length of the grating in \( x \). Using the convolution theorem, the Fourier transform becomes,

\[
P_f^g(\beta, z) = \sum_j P_j(z) \delta(\beta - (\beta_{\text{inc}} + \frac{2\pi m}{\Lambda})) \otimes F(G(x)) \otimes F(\text{Rect}(x/L)) \tag{2.35}
\]

where \( F \) Fourier transforms the functions in brackets. As the Fourier transform of a Gaussian is another Gaussian and the Fourier transform of a Rect function is a sinc function, the resulting \( P_f^g(\beta, z) \) is an infinite series of peaked functions (Gaussians convolved with sinc functions) separated by \( 2\pi/\Lambda \). The infinite weak grating coupling condition, \( \beta_{\text{inc}} + j \frac{2\pi}{\Lambda} = \beta_{\text{mode}} \), is no longer strict because \( \beta_{\text{mode}} \) can lie slightly away from the peak at \( \beta_{\text{inc}} + 2\pi m/\Lambda \) where \( P_f^g(\beta, z) \) is now non-zero due to the broadening. The smaller the extent of the polarization in space, the wider becomes the bandwidth of the grating coupler. The bandwidth describes the range of frequencies over which the fraction of light coupled into the slab exceeds a chosen value for excitation at the optimal coupling angle.

Similarly, slab modes incident from the waveguide onto a finite grating will induce a periodic polarization over only a finite distance. This is in part due to the finite length of the grating, but also due to the decay of the mode strength due to light radiating out of the slab as it propagates. The grating polarization for out-coupling becomes

\[
P_g^f(\beta, z) = \sum_j P_j(z) \delta(\beta - (\beta_{\text{mode}} + 2\pi m/\Lambda)) \otimes F(e^{-\alpha x}) \otimes F(\text{Rect}(x/L)) \tag{2.36}
\]

As the Fourier transform of a decaying exponential is a Lorentzian, once again the resulting \( P_g^f(\beta, z) \) is a series of peaked functions separated by \( 2\pi/\Lambda \). As there is some range of non-zero \( P_g^f(\beta, z) \) near \( \beta = \beta_{\text{mode}} + 2\pi/\Lambda \) light will no longer radiate away from the grating at discrete angles, but will radiate over a range of angles.

While weak gratings can be used to couple light into and out of bound slab modes, they have a number of undesirable characteristics. To efficiently couple light into the gratings, the gratings must be illuminated over a large area to maximize the grating polarization response.
Illumination over a wide area causes the gratings to have narrow bandwidths which restricts the frequency and angle tuning ranges possible for coupling. A large grating area is also required for collecting the light slowly diffracted from a bound mode. This results in a narrow bandwidth and takes up valuable real estate on the chip. In summary, to use weak gratings efficiently, they must cover a large area and they have narrow coupling bandwidths. In the next section, we will see that when the grooves of the weak grating are extended deep into the slab, the grating polarization response is enhanced and these gratings can be more compact and can couple light over larger bandwidths.

2.3 Strong Grating Couplers

A strong grating has periodic texturing that extends deep into the slab, and so its effect on the electrodynamics goes well beyond what can be treated using a weak perturbation analysis. For the reasons explained above, the etch should be entirely through the silicon slab layer so that the grating coupler can be fabricated in a single-step process with other photonic device elements such as photonic wires and photonic crystal structures. In this section, one dimensional strong gratings with infinite and finite extents will be studied using band structure concepts, rather than perturbation theory. Two dimensional gratings couplers are discussed at the end of this section.

2.3.1 1D Strong Grating Coupler

2.3.1.1 Strong Grating Bandstructure

The infinite 1D strong grating illustrated in figure 2.9 has periodicity $\epsilon(r + m\Lambda \hat{x}) = \epsilon(r)$ through the slab. This structure is often called a 1D photonic crystal slab. To help determine the analytic form of the modes $(H(r))$ that may be supported by the structure, translation operators will again be used. Like the untextured slab, the grating has translational invariance in the $\hat{y}$ direction. There is now discrete translational invariance in the $\hat{x}$ direction.
The eigenvalue problem for the discrete translation operator, $T_{m\Lambda}$, with $\Lambda = \hat{\Lambda} \hat{x}$ is,

$$T_{m\Lambda} e^{ik_x x} e^{ik_y y} f(z) = e^{ik_x (x+m\Lambda)} e^{ik_y y} f(z) = e^{ik_x m\Lambda} e^{ik_x x} e^{ik_y y} f(z) \quad (2.37)$$

In this case, there are multiple solutions to (2.37) with the same $k_x$ eigenvalues. These are the solutions with $e^{i(k_x + \frac{2\pi q}{\Lambda}) x}$ where $q$ is an integer. The wavevector increment, $b = \frac{2\pi}{\Lambda} \hat{x}$ is often called a reciprocal lattice vector. For this grating problem, a mode labelled by $k_x$ and $k_y$, which also satisfies the $\Theta$ eigenvalue problem, will be constructed as the sum of solutions to (2.37) that share the same eigenvalues.

$$H_{n,k_x,k_y}(r) = e^{ik_y y} \sum_q f_{k_x,q}(z) e^{i(k_x+q b)x} = e^{ik_y y} e^{ik_x x} u_{k_x}(x,z) \quad (2.38)$$

This result, called Bloch’s theorem, has a similar form as the wavefunction of an electron in a periodic potential [23]. Unlike the slab modes, these modes are now harmonic waves propagating in the $x$-$y$ plane with periodic modulation in $x$ and non-periodic modulation in $z$. It is important to recognize that a grating mode $H_{k_x,k_y}(r)$ is physically identical to $H_{k_x+qb,k_y}(r)$. Therefore it would be redundant to consider solutions over a range larger than one reciprocal lattice vector. This redundancy can be avoided by plotting the band structure for $-\pi/a < k_x < \pi/a$ as is shown in figure 2.10. This range is called the 1st Brillouin zone. As propagation along the $\hat{x}$ direction is of interest, $k_x$ will be labelled as $\beta$ to keep the same notation as was used in the untextured slab band structure discussion.
As with the untextured slab case, there are multiple mode solutions with the same $\beta$ with discretely separated energies labelled by $n$. There are also different modes for TE and TM polarizations. Only one of these modes is shown schematically in figure 2.10.

![Figure 2.10: Band diagram for a 1D photonic crystal slab as in figure 2.9. The straight dashed and dotted lines are the substrate and bulk dielectric light lines respectively. A continuum of radiation modes exists in the shaded region above the substrate light line as well as quasi-bound modes (solid curved lines). Purely bound modes (dotted curved lines) exist below the substrate light line. Beyond the first Brillouin zone ($\beta = -\pi/a$ to $\pi/a$) lie modes (dash double dot lines) in the extended zone scheme. The star marks a mode with a negative group velocity. This diagram is modified from [13].](image)

This structure supports both pure- and quasi-bound modes. Pure-bound modes (dotted curved lines in figure 2.10) have every Fourier component below the substrate light-line. Quasi-bound modes (solid curved lines) have one or more Fourier components that lie above the substrate and/or superstrate light-line. The quasi-bound, or “leaky modes” with one (typically) or more Fourier components above the air light-line are used for grating coupling. These modes lie at higher energy than the untextured slab bound modes they are derived from, because mode patterns of the strong grating have a greater field concentration in air. The significance of the gaps between the modes at the band edges (0 and $\pi/\Lambda$), called band gaps, is discussed in section 2.4. This strong grating structure also supports a continuum of modes above the substrate light-line, none of which are preferentially localized in the slab.
region, unlike the bound and quasi-bound modes.

It is also important to note that unlike the slab mode case, the sign of $\beta$ does not disclose the direction of propagation of the mode. The star in figure 2.10 marks a partially bound mode that has a Fourier component $k_x$ above the air light-line in the upper half of the first Brillouin zone (i.e. $\beta = 0$ to $\pi/\Lambda$) and another component with negative $k_x\hat{x} + m\hat{b}$ below the light line. These components propagate in opposite directions. The modulation function, $u_\beta(x, z)$, includes all the Fourier components of a mode so that it no longer has identifiable phase fronts from which the phase velocity, $\omega k/k^2$, can be trivially determined. Instead, it is the group velocity, $v_g$, which informs the direction and speed of energy propagation. The group velocity of a mode is given by,

$$v_g(k) = \frac{\partial \omega}{\partial k_x} \hat{x} + \frac{\partial \omega}{\partial k_y} \hat{y} + \frac{\partial \omega}{\partial k_z} \hat{z} \quad (2.40)$$

In the upper half of the first Brillouin zone ($\beta = 0$ to $\pi/\Lambda$), negative group velocities are associated with negatively sloped bands and describe partially bound modes with lossy Fourier components that propagate in the direction opposite of the bound Fourier component.

For the photonic crystals studied in this thesis, time reversal arguments it can be used to easily show that $\omega(\beta) = \omega(-\beta)$ and consequently $v_g(\beta) = -v_g(-\beta)$. With this symmetry in $\beta$, it is sufficient to plot the band structure over $\beta = 0$ to $\pi/a$.

A plane wave incident from air on the infinite strong grating at an angle $\theta$ to the normal excites a partially bound mode with $\beta_{mode}$ when

$$\frac{\omega}{c} \sin \theta + 2\pi m/\Lambda = \beta_{mode} \quad (2.41)$$

This corresponds to a buildup of field strength in the slab that is considerably higher than the incident field strength. When this condition is not met, the incident light diffracts, exciting modes within the continuum, and there is no field enhancement in the vicinity of the slab.
2.3.1.2 Strong Grating Couplers of Finite Extent

A strong grating coupler of finite extent used to couple light into bound modes of an untextured slab waveguide is illustrated in figure 2.11. As just mentioned, a beam that is focused on the grating with \( \frac{\omega}{c} \sin \theta = \beta_{\text{mode}} \), will excite a partially bound mode of the grating region with \( \beta_{\text{mode}} \), which decays as it propagates due to the light radiating out of the slab. If the grating mode has not fully decayed when it reaches the grating-slab interface, a bound slab mode may be excited. This excited slab mode will have the same energy as the grating mode but in general the \( \beta \) of the bound slab mode that takes energy away from the grating will not be equal to \( \beta_{\text{mode}} \). This is illustrated in figure 2.12 where the band structure for a grating (\( \Lambda = 795\text{nm}, t = 220\text{nm}, \) groove width = 300nm) and the dispersion of a slab suspended in air (\( n_{\text{sub}} = 1 \)) are compared in the extended zone scheme. The line crossing the grating band represents frequency tuning of light incident at a fixed angle, which is discussed near the end of this section. As a result of the \( \beta \) mismatch and the difference in the mode profiles of the grating and slab modes, at the interface, a fraction of the light will reflected back into a grating mode and the rest will be transmitted into the slab mode. This can be compared to the simple case of a plane wave travelling in the \( \hat{x} \) direction hitting an interface between medium \( a \) and \( b \) with different refractive indexes at normal incidence. The Fresnel reflection coefficient is,

\[
r = \frac{n_a - n_b}{n_a + n_b}
\] (2.42)
Figure 2.12: Comparison of the band structure of a strong grating ($\Lambda = 795$nm, silicon thickness $= 220$nm, groove width $= 300$nm) in the extended zone scheme to the dispersion of an untextured slab, both are suspended in air (no substrate). Dashed horizontal arrow helps show the $\beta$’s for grating and slab modes at the same energy, whose difference causes impedance mismatching. The blue line represents the frequency tuning of the incident in-plane wavevector (shifted by $\frac{2\pi}{\Lambda}$), $\beta_t$, for light incident at 20°, so that $\beta_t = \frac{\omega}{c} \sin 20^\circ + \frac{2\pi}{\Lambda}$. Coupling from air to a grating mode is strongest at the tuning line/grating band overlap point, marked with a circle.

The grating and slab modes with $\beta_g$ and $\beta_s$ have effective refractive indexes $n_g$ and $n_s$ where $\beta = \frac{\omega}{c} n_{eff}$. The reflection of the grating mode at the grating-slab interface will depend on the discrepancy in $n_g$ and $n_s$. Due to this effect, the more the grating dispersion deviates from the slab dispersion, the weaker the coupling will be between the grating mode and the slab mode.

The finite extent of the grating, the localized excitation spot size, and the intrinsic decay length due to the leaky nature of the modes all contribute to broadening the bandwidth of the strong grating couplers. The modes supported by a finite grating at a given frequency cannot be described by discrete $\beta_{mode}$’s as in the infinite grating case, because broadening introduces a spread of fourier components around each $\beta_{mode}$. The broadening effects are qualitatively the same as for finite size weak grating couplers, as discussed in section 2.2.1, but the extent of broadening is typically much larger due to the enhanced leakiness of most
quasi-bound modes in deep-etched gratings. This means strong gratings can typically be made smaller, and exhibit larger bandwidths than weak gratings, both for input and output coupling.

It is important to note that a forward propagating incident wave will not necessarily excite a forward propagating bound mode. As was previously discussed, the lossy and bound Fourier components of a mode propagate in opposite directions when the band of the mode is negatively sloped in the upper half of the first Brillouin zone. If this type of mode is excited, the bound component will propagate backwards. Similarly, for out-coupling, the slab mode couples to a grating mode which radiates light backwards out of the slab. This phenomena is called back-coupling. When lossy and bound Fourier components propagate in the same direction, it is possible to forward-couple light into and out of the grating.

In the grating coupling experiments done in this thesis, the angle of incidence is set and the frequency is swept over a range of energies (roughly 6200-6600cm\(^{-1}\)). To represent this frequency tuning of incident light on a band structure diagram, one can plot \( \beta_{\text{inc}} = \frac{\omega}{c} \sin \theta \). It is sometimes more useful, to translate this tuning line to the extended zone scheme. Frequency tuning is shown in figure 2.12 where \( \beta_t = \frac{\omega}{c} \sin 20^\circ + \frac{2\pi}{\Lambda} \) is plotted in the vicinity of a grating band. At energies away from the grating band/tuning line overlap point, \( \beta_t \) is different from the grating band \( \beta_{\text{mode}} \). As discussed above, finite grating modes have a spread of Fourier components about \( \beta_{\text{mode}} \). This makes it possible to excite a grating mode away from the overlap point when \( \beta_t = \beta_{\text{mode}} + \Delta \). However, for large \( \Delta \), the grating mode Fourier component \( \beta_{\text{mode}} + \Delta \) is relatively weak, leading to reduced coupling compared to when the broadening is not required for coupling. The tuning line is much steeper than the grating band dispersion and coupling to grating modes quickly becomes weaker away from \( \beta_t = \beta_{\text{mode}} \). This effect causes the grating coupling spectra to be peaked at \( \omega = \frac{\omega}{\sin \theta} \left( \beta_{\text{mode}} - \frac{2\pi}{\Lambda} \right) \).

Finally, all of the above “momentum matching” discussion applies independently to S(P)-polarized incident radiation as it couples to TE(TM)-slab mode derived grating modes, which in turn excite TE(TM) polarized slab modes.

To conclude this section, an alternative, but still qualitative and more intuitive explanation of grating coupling light into a slab is offered. Consider the 1D finite grating structure
in figure 2.11. An externally driven line of dipoles extending along the $y$ direction, and oscillating at a frequency $\omega$ inside the grating will excite an electric field that satisfies the inhomogeneous Maxwell’s equations for the full textured structure at $\omega$. At any $\omega$, this field will always contain non-localized radiation modes within the shaded continuum in figure 2.10. Depending on $\omega$, it may also include one or more bound and/or quasi bound modes, as indicated in figure 2.13. In this discussion, quasi-bound modes relevant to grating coupling are excited, in which case the field excited by the line of dipoles decays as it propagates with a phase given by $\beta_{\text{grating}}(\omega)$.

A finite size beam of frequency $\omega$ incident in the $x-z$ plane with in plane wavevector $\beta_x$, will drive a localized distribution of line dipoles with well defined relative phase in the $\hat{x}$ direction. The phase of the field driven by each line of dipoles separated by a distance $\Lambda$ in $x$ is identical when $\beta_x + \frac{2\pi}{\Lambda} = \beta_{\text{grating}}$. In this case, the maximum possible net field is excited beneath the excitation beam, and it will extend beyond the excitation beam profile by the quasi-bound mode’s decay length. This is illustrated in the left plot of figure 2.14 where the decaying fields generated by in-phase dipoles separated by $\Lambda$ in $x$ are plotted
individually (red), as well as their net field (blue). If there is a phase mismatch of $\beta_x$ and $\beta_{\text{grating}}$ so that $\beta_x + \frac{2\pi}{\Lambda} \neq \beta_{\text{grating}}$, the quasi-bound fields excited by adjacent lines of dipoles separated by $\Lambda$ will gradually go out of phase over a lateral distance $\Delta x = \frac{1}{\alpha}$, where $\alpha$ is the decay rate (in $x$) of a grating mode, as is illustrated in the right plot of 2.14. Thus the smaller the grating, as limited by the quasi-bound mode decay length, the larger is the tolerable mismatch in the in-plane wavevectors before efficient generation of fields is defeated by destructive interference. This tolerable range of $\Delta \beta_x$ is directly related to the bandwidth of the coupler. As described above, if the excited partially bound mode reaches the slab interface without having fully decayed, it will couple to a bound slab mode.

Figure 2.14: Schematic of the phase (represented by cosine modulation) and decay of grating modes driven by dipoles, separated by $\Lambda = 795\text{nm}$ in $x$, that were excited by a plane wave in the $x-z$ plane with $f = 186\text{THz}$ and an incident angle $\theta = 35^\circ$ (left plot)/$\theta = 10^\circ$ (right plot). The net fields are plotted in blue. Fields are offset for clarity. The positions of the dipoles are indicated at the top of the plot (circles). The grating mode has $\beta_{\text{grating}} = 2.7\frac{\pi}{\Lambda}$ and a decay length, $\frac{1}{\alpha} = 2\mu\text{m}$. The phase matching condition for maximum net field is met in the left plot, and there is phase mismatching in the right plot, $\Delta \beta_{\text{inc}} = 1.6 \times 10^6$ (the black lines at $x = 0$ help guide the viewing of relative phases).
2.3.2 2D Rectangular Strong Grating Coupler

The gratings discussed up to this point have periodicity in one direction. However, those studied experimentally in this thesis have a rectangular lattice, that is $\epsilon(r + ma_x \hat{x} + na_y \hat{y}) = \epsilon(r)$. They are 2D photonic crystal slabs consisting of a dielectric slab with a rectangular lattice of air holes, as illustrated in figure 2.15.

![Figure 2.15: A dielectric slab sitting on a substrate with a rectangular lattice of air holes forming a 2D photonic crystal grating coupler.](image)

Following the same logic presented in section 2.3, the introduction of periodicity into a second dimension results in modes with the form:

$$H_{n,\beta}(r) = e^{i\beta \cdot \rho} u_{n,\beta}(\rho, z)$$ (2.43)

where $\beta$ and $\rho$ are in the $x-y$ plane and $H_{n,\beta}(r) = H_{n,\beta + m2\pi/a_x \hat{x} + n2\pi/a_y \hat{y}}(r)$. This band-folding, which is required for grating coupling, is now present in both $x$ and $y$. This makes it possible to grating couple light into modes with

$$\beta_{inc} + 2\pi m/a_x \hat{x} + 2\pi n/a_y \hat{y} = \beta_{mode}$$ (2.44)

when polarization matching is satisfied. For light incident with $\beta_{inc}$ in the $\hat{x}$ direction, the second direction of periodicity allows light to couple to slab modes travelling off the $\hat{x}$ direction, even orthogonal to it. However, in this thesis, the coupling geometry is chosen such that the grating effectively acts like a 1D grating structure. In this case, $\beta_{inc} = \beta_{inc} \hat{x}$ and only forwards and backwards coupling in $\hat{x}$ are significant.
2.4 Photonic Bandgap Structures

Waveguides and microcavities residing in photonic crystals, discussed in chapter 1, exploit the photonic band gap properties of the periodically textured slab. In 3D textured dielectrics, it is possible to engineer the structure to exhibit a photonic band gap, which is a range of frequencies over which there exist no modes and light is prohibited from propagating. In the planar slab geometry there can never be a complete photonic bandgap because there are always continuum radiation mode solutions of Maxwell’s equations at all frequencies (the shaded region of figure 2.10). However, there can be pseudo photonic band gaps for TE and TM polarized bound and quasi-bound modes when appropriate, strong 2D texture is introduced in the slab. These pseudo photonic band gaps for the slab geometry correspond to ranges of frequency where no bound or quasi-bound modes of a specified polarization exist.

The devices encountered in this thesis, described in chapter 1, include photonic bandgap structures in a 2D hexagonal lattice of holes in a silicon slab. The uniformly textured slab is designed to have a relatively large pseudo first order photonic band gap for TE polarized light, centered around 1.5\( \mu \)m. As discussed in chapter 1, an L3 microcavity can be formed by omitting three adjacent holes in the hexagonal lattice, as was shown in figure 1.5a. The photonic crystal defect acts as an optical cavity where TE polarized light with a specific frequency inside the pseudo band gap reflects off the surrounding crystal and constructively interferes so that a standing wave mode exists in the defect region and evanescently decays into the crystal. Similarly, removing a row of holes creates a waveguide for a range of frequencies in the pseudo band gap, as is shown in figure 1.5b. In both cases, light is confined in-plane by the photonic crystal and out of plane by total internal reflection off the dielectric-air interface (below the light line).

When photonic crystal waveguides are placed on either side of a microcavity, as illustrated in figure 1.6b, light can be coupled into and out of the microcavity via the waveguide modes. Transmission from one waveguide to the other is highest on resonance, much like the transmission through Fabry-Perot cavity consisting of two reflectors. The transmission
has a Lorentzian lineshape [14] with a full width at half maximum (FWHM) linewidth that is inversely proportional to the lifetime of the photons in the cavity. The quality factor of a cavity, $Q$, is a measure of this lifetime described in terms of the optical period and may be expressed as,

$$Q = \frac{\omega_0}{\Delta \omega_0} \quad (2.45)$$

where $\omega_0$ is the resonance frequency of a cavity mode and $\Delta \omega_0$ is FWHM of the transmission peak. The quality factor depends on the strength of the coupling between the cavity and the waveguides as well as the amount of out-of-plane leakage.

### 2.5 Numerical Simulations

Analytic solutions of the inhomogeneous Maxwell’s equations for the response of most non-perturbative or deep-etched structures are unavailable. In these cases, it is common to turn to numerical solution methods. Two methods used in this thesis to solve for electric and magnetic fields are discussed in this section.

One method is finite difference time domain (FDTD) analysis, in which a simulation volume which contains the structures and sources of interest is divided into Yee cells, named after Kane Yee who first proposed this method [25]. Each Yee cell has a specified $\epsilon$ (assuming $\mu = 1$) and the cells are arranged on a grid of regularly spaced points where the electric and magnetic fields are updated in time steps determined by the operating frequency and grid spacing. To solve for the discrete fields, the time-dependent Maxwell’s equations,

$$\frac{dD}{dt} = \nabla \times \mathcal{H} \quad (2.46)$$

$$\frac{d\mathcal{H}}{dt} = -\frac{1}{\mu_0} \nabla \times \mathcal{E} \quad (2.47)$$

are converted to a set of difference equations that explicitly relate field components at different locations in space and points in time. Applying the appropriate boundary conditions, these equations may be solved iteratively to find the time evolution of the fields. Solutions obtained using modern commercial FDTD algorithms are “exact” to within the discretization
level used.

Commercial software makes it possible to employ the FDTD method using a user-friendly interface. The software used in this thesis, Lumerical FDTD Solutions, has a graphical interface in which a simulation may be set up in 2D (where the fields are considered unchanging in one direction) or 3D. A mixed material structure can be constructed using a combination of preset and custom objects with materials chosen from an extensive database containing frequency dependent optical properties of common materials. The spectral properties, polarization and location of sources (plane wave, dipole, Gaussian beam, etc) included in the simulation may also be chosen. The meshing of the simulation volume, which determines the density of points at which the fields will be evaluated, must be chosen so that the field varies slowly from point to point for accurate results. The boundary conditions for the faces (or edges, in 2D) of the simulation volume must be appropriately chosen based on the nature of the problem to be solved. Fields propagating in a homogeneous material towards a simulation volume boundary can “pass” through unreflected by applying Perfectly Matched Layers (PML) boundary conditions, an algorithm which adds a highly absorptive artificial material designed for impedance matching with its surroundings. The number of iterations, or the time duration of the simulation (often in femtoseconds), must also be tailored to the type of simulation to obtain useful results. The capabilities of FDTD are limited, as simulations typically have high memory requirements and long computing times when the simulation volume contains objects with large variation in sizes (e.g. 500nm diameter photonic crystal holes and a 14µm wide waveguide).

For large structures with bound propagating modes, such as the tapered waveguides in our structures, finite difference frequency domain (FDFD) methods may be used to compute solutions more efficiently than FDTD methods [39]. The effective indexes of the modes with frequency $\omega$ supported in a cross-section of a waveguide may be found by meshing the 2D surface and discretely solving Maxwell’s equations. Imposing a mode frequency and a propagation axis normal to the surface, the equations reduce to solving a matrix eigenvalue problem from which the mode indexes and mode profiles can be retrieved. Lumerical offers an Eigenmode Solver software, MODE Solutions, that applies this method. The 2D
simulation may be set up similar to FDTD and results may be imported between the two software packages. In addition to the Eigenmode Solver, MODE Solutions offers propagation algorithms that make it possible to incrementally propagate a field down an arbitrarily shaped waveguide. A 3D waveguide is approximated by a series segments with slowly varying waveguide cross-sections. A field composed of modes of a waveguide cross-section (found using the Eigenmode Solver) is propagated the length of a segment and is then decomposed into the modes of the next waveguide segment. The algorithm includes the calculation of an overlap integral between the original waveguide modes and the new modes. The fraction of power that may be coupled into the next section depends on the overlap integral and the difference in the effective indexes of the modes. The rest of the power is reflected. The final field profile may be found at the end of the waveguide once multiple iterations are complete.
Chapter 3

Devices

In this section, the devices studied in this thesis are described. Thousands of these devices are fabricated on a single 200mm diameter silicon-on-insulator (SOI) wafer. The design of the devices is discussed in addition to the chip and wafer layouts. Post-fabrication processing done to improve the devices is also described.

3.1 Design Layout

The design of the devices studied in this thesis is based on experimental and theoretical work previously done in this lab [6]. The features of the design are etched through the 220nm thick top silicon layer of a silicon-on-insulator (SOI) wafer with a 2µm thick substrate of silica (SiO$_2$) and a silicon base. The original design, illustrated in figure 3.1, includes three key elements: i) input/output grating couplers, ii) waveguides, and iii) a microcavity. The cavities are symmetrically coupled to input and output single mode waveguides, which couple light into tapered waveguides that are terminated by photonic crystal gratings couplers. The grating couplers act as input/output ports, as they couple light between free space (above the sample) and the tapered waveguides. When one grating coupler is excited from free space at the resonant frequency of the cavity mode, a large intensity of light builds up in the cavity and light is transmitted through the entire waveguide/cavity structure to the output grating, where it is diffracted off the chip. A rectangular lattice of holes (hole diameters
Figure 3.1: Schematic of a device (not to scale). The grating couplers couple light into and out of the device. The waveguides allow light to couple to the L3 cavity modes.

\(\lambda = 480\text{nm}\) is designed to form a photonic crystal grating coupler that couples light from free-space into the tapered ridge waveguide. The pitches along the waveguide axis direction and perpendicular direction are 795nm and 750nm with 25 and 29 periods respectively. A 300 \(\mu\text{m}\) long parabolically tapered multi-mode waveguide, with a width slowing changing from 14 \(\mu\text{m}\) to 450nm, is used to efficiently couple light from the grating into a single-mode ridge waveguide. The modes supported by the adiabatic tapered waveguide have mode profiles and effective indices \((n_e)\) that change slowly along the propagation axis, making for good impedance-matching and low reflections. The single mode waveguide is designed so that its TE mode couples well to a hexagonal photonic crystal TE waveguide mode, which also requires good matching of the mode profiles and effective indices, to minimize reflections at the interface. The photonic crystal waveguide is designed to couple resonant light into an L3 cavity, as shown in figure 1.5a in chapter 1. The cavity quality factor is strongly dependent on the strength of this waveguide coupling, which is controlled by the placement of two holes adjacent to the cavity defect region. This can be compared to a Fabry-Perot cavity formed by two adjacent reflectors, where light is transmitted through the back of one reflector, enters the optical cavity and undergoes multiple reflections, while a fraction of light inside the cavity is transmitted outside the cavity, through the second reflector. The quality factor of the cavity and the transmission of light out of the cavity depend on how much light is reflected/transmitted at each interface.

The SOI wafer consists of an array of chips, commonly called dies, as shown in figure 3.2a. Each 14 mm by 10 mm chip consists of multiple devices that have different hexagonal
Figure 3.2: a) Layout of chips on half of the wafer. Columns and rows are alphanumerically indexed. b) Layout of devices on each chip. Devices are indexed by their row (R), column (C) and shift (s). Arrows point in the direction of increasing quantities.
photonic crystal parameters: hole size, pitch and hole shift. The devices are grouped in sets of six (see figure 3.2b) with the same the hole size and pitch, but with the two holes at either ends of the L3 cavity shifted from 0 to 50nm as shown in figure 3.3. Each chip has a 9 by 7 array of these groups. Grating couplers of adjacent devices are separated by 195µm. For the first six columns, the hole diameter varies by 10nm increments from row to row and the pitch varies by 5nm increments from column to column. The hole diameters on the chip vary between 280nm and 160nm and the pitch varied between 425nm and 400nm. The gratings and waveguides remained the same across the first five columns while the waveguide lengths are varied in the last column. The devices on each chip are labelled by their row (R), column (C) and shift (s) as in figure 3.2b.

3.2 IMEC Fabrication

Fabrication of the devices was done at the Inter-University Microelectronics Center (IMEC) in Leuven, Belgium. This foundry uses CMOS fabrication equipment to process 200mm diameter SOI wafers. The designs were submitted to the foundry through CMC Microsystems, a company that prepared the design files with the necessary processing information.

Deep ultraviolet lithography and a chemical etch are to pattern the top silicon layer of the wafer [8]. The fabrication procedure is illustrated figure 3.4. A layer of photoresist is spin-coated on the SOI (figure 3.4b) followed by an anti-reflection (AR) coating (figure 3.4c). This coating reduces reflections at the air-resist interface and helps eliminate thin film interference in the resist layer that can lead to nonuniform illumination. An optical stepper is used to
Figure 3.4: Device fabrication procedure steps. a) SOI wafer b) Spin-coated photoresist c) Spin-coated AR coating d) UV light exposure by an optical stepper e) Photoresist developed f) Chemical etch of top Si layer e) Removal of photoresist (final device)

illuminates the photoresist with $\lambda = 248$nm light (figure 3.4d), so that upon development, the photoresist acts as a mask for the silicon chemical etch (figure 3.4e). The sizes of the mask features critically depend on the exposure dose used for illumination and the optical stepper design pattern, which together can yield unpredictable results. The exposure dose is varied across the wafer from column to column in order to obtain desired feature sizes for chips within a certain region on the wafer. A plasma treatment is used to harden the resist before undergoing a chemical etch to remove the desired silicon (figure 3.4f). The resist is then removed from the surface of the etched silicon (figure 3.4g). Optical microscope images of a chip are shown in figure 3.5.

A scanning electron microscope (Hitachi S-4700 FESEM) is used to obtain images with higher magnification and greater detail. An image of a grating coupler connected to a tapered waveguide is shown in figure 3.6a and an image of an L3 cavity within a photonic crystal waveguide, and ridge and tapered waveguides is shown in figure 3.6b. Images of grating coupler holes, like those shown in figure 3.7, are taken for multiple devices on different chips. The known grating pitch is compared to the pitch measured using the scale bar in an image like figure 3.7b to determine the appropriate scaling factor. Applying this scaling, the hole sizes are measured with $\pm 6$nm uncertainty. The measured hole diameters vary by $\pm 2$nm within the same grating and $\pm 5$nm among different gratings on the same chip. The average hole diameters for chips from different columns on the wafer are plotted in figure 3.8. Note that these hole sizes are all larger than the 480nm design diameter. The implications
of this will be discussed in section 3.3. In the illumination process, the exposure is set to remain constant along each column, but it varies from column to column, as in figure 3.2a. Experimental resonant cavity transmission measurements of “identical” devices on two different chips from the same column on the wafer, are reported in chapter 7 to have almost identical resonance frequencies (within $5\text{cm}^{-1}$), confirming consistent exposure dose along the column. Similar results are reported, in chapter 6, for grating coupler measurements taken for “identical” devices on two different chips from the same column. The hexagonal photonic crystal hole diameters are approximately equal to their design values in the 8th column of chips on the wafer, with the exception of the holes lining the waveguide and the cavity, which are approximately 10% larger due to optical proximity effects [15]. The hole diameters deviate from the design values away from the 8th column (larger holes for low numbered columns).
3.3 Post-Fabrication Sample Treatment

As many applications explored in this lab require cavities with moderately high quality factors (thousands), the samples from IMEC undergo further treatment to reduce the rate of out-of-plane leakage. This processing, summarized in table 3.3, involves using photolithography and wet-etching to locally remove the buried oxide layer below the cavity region, causing an increase in the index contrast at the slab-air interface.

The bare sample is first coated with a thin layer of HMDS primer. Testing showed that a 2µm coating of resist can be spun on the sample using a Headway PWM32 Spinner using the following recipe: ramp up at 500rpm/s, spin at 1700rpm for 40s then ramp down at 500rpm/s. After the HMDS and photoresist are applied, the sample is soft baked at 90 °C for 10 minutes before UV photolithography is used to remove the resist over the photonic
crystals. The photolithography is done with a Karl Suss MJB3 Mask Aligner which is used to align a mask over the sample and expose it for 45s to 320nm light at 22mW/cm². The mask is designed to let light through seven 5µm wide strips over entire columns of the photonic crystals in a given chip, leaving the waveguides and grating coupler covered. An overlay of an image of the mask and an image of a chip is shown in figure 3.9. The mask was made externally by a member of Prof. Carl Hansen’s lab using an LW405 Laser Mask Writer. After exposure, the sample was developed for 90 seconds in an AZ P4110 developer solution (1:4, developer : DI water) to remove the exposed resist. The sample was then hard baked for 10 minutes at 120 °C. An optical microscope image of the sample after all of these steps is shown in figure 3.10.
<table>
<thead>
<tr>
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<th>Step</th>
<th>Procedure</th>
<th>Time Duration</th>
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<tr>
<td>Spin-coating</td>
<td>1</td>
<td>Cover with HMDS Primer</td>
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<tr>
<td></td>
<td>2</td>
<td>Ramp up at 500 rpm/s</td>
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<td>3</td>
<td>Spin at 1700 rpm</td>
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<td>4</td>
<td>Spin down at 500 rpm/s</td>
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<td>Let HMDS dry</td>
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<td>Cover with AZ P4110 photoresist</td>
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<td>7</td>
<td>Repeat steps 2 to 4</td>
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<td>8</td>
<td>Soft bake at 90°C</td>
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<tr>
<td>Undercutting</td>
<td>14</td>
<td>Emerse in HF solution (10 parts 40% NH₄F to 1 part 49% HF)</td>
<td>15-20min</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Rinse with DI water and dry with N₂ gas</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Summary of post-fabrication processing recipe.

The silicon dioxide is then removed below the photonic crystal by leaving the hard baked sample in an HF solution (10 parts 40% NH₄F to 1 part 49% HF) for 20 minutes. The effect of this process, also called undercutting, on the resonant transmission spectrum is discussed in chapter 7. While the remaining photoresist can then be removed using acetone and isopropyl alcohol, this is not done in most cases as it functioned as a means for correcting fabrication errors in the grating coupler hole size. Due to the deviation of the hole diameters from those specified in the design, for many of the chips, light cannot be coupled into the waveguides via uncoated gratings at frequencies within the tuning range of the laser used in experiments, which is also the range of the cavity resonance frequencies on the wafer. To shift the energy of the grating coupler spectra into a functional range, the layer of AZ P4110 photoresist is not removed after photolithography. With photoresist on the surface of the gratings, the mode energies are lower than what they would be in air, as demonstrated in chapter 6, which compensates for the erroneously large hole sizes.
Figure 3.10: Optical microscope image of a sample after undergoing photolithography. The grating couplers and waveguides are coated with resist while the photonic crystals are bare.
Chapter 4

Simulations

In this chapter, results of several different types of simulations, relevant to the grating-to-grating measurements done in this thesis, are presented. To provide a semi-quantitative, but relatively intuitive introduction to grating coupler analysis, the band structure of a deep-etched 1D grating structure (simpler than the 2D device gratings), calculated using FDTD Solutions, is reported in section 4.1. The quantitative, full numerical simulation of the grating-to-grating experiments described in chapters 2 and 6, is broken into three parts: i) excitation of slab modes by light incident on an input grating coupler, ii) propagation of slab modes over a given distance between the input and output gratings and, iii) diffraction of the slab modes via an output grating coupler.

4.1 1D Band Structure

In section 2.3 of chapter 2, the band structure of strong gratings and its relevance to grating coupling was discussed. The band diagram of a grating structure reveals which frequencies and incidence angles may be used to excite grating modes, which in turn excite untextured slab modes. In the first Brillouin zone, the slopes of the TE and TM bands indicate whether forward or backwards coupling geometries, as in figure 2.1, are required for coupling at a given frequency.

In this section, Numerical FDTD Solutions simulations, are used to approximate the
grating bandstructure for the TE and TM grating modes with in-plane wavevectors along the large-period direction of the actual 2D gratings. The structure, illustrated in figure 4.1, is a 220nm thick silicon slab suspended in air with 300nm wide lines etched through the Si, and a pitch, $\Lambda = 795\text{nm}$, which is the same as the on-axis pitch of the device gratings (see chapter 3), and the same fill factor (the fraction of the grating volume occupied by silicon), 62.3%, as a 2D grating with holes of diameter 535nm. The substrate is omitted to simplify the solution of the exact eigenmode dispersion. To find the modes of this structure, which extends uniformly to infinity in $y$ and periodically to infinity in $x$, a 2D FDTD simulation in $x$ and $z$ is used. As is described in section 2.5, the FDTD simulation includes the structure of interest, sources and monitors, inside a simulation volume. A single unit cell of the structure (spanning one $\Lambda$ in $x$) is included in the simulation volume and Bloch boundary conditions in $x$ are applied to impose:

$$E_\beta(x, z) = f_\beta(z) e^{i\beta x} u_\beta(x, z)$$

(4.1)

where $u_\beta(x + \Lambda, z) = u_\beta(x, z)$. This is the result from (2.39) with $k_y = 0$. To generate the band structure, a simulation is done for various $\beta$ values in the first Brillouin zone. Broadband sources excite modes supported by the structure (subjected to the condition in (4.1)) and time monitors detect the field evolution over the simulation time (extending well past the dipole excitation pulses). The monitor data is then analyzed to find the mode frequencies. Ten point-electric-dipole broadband sources are randomly distributed within

Figure 4.1: Illustration of the 1D grating structure for which the band structure is simulated. The grating consist of a silicon slab suspended in air, with periodic grooves extending through the silicon. A unit cell of the structure, in which the fields were calculated, is outlined and has a pitch equal to the on-axis pitch ($\Lambda = 795\text{nm}$) of the 2D grating structures studied experimentally in this thesis.
Figure 4.2: Schematics of the simulations used for the 1D band structure calculations of a) TE modes and b) TM modes. The simulation area spans a unit cell of the grating and contains point-electric-dipole sources and field time-monitors. Each schematic shows a single dipole, oriented in $y$ for the TE simulation and in $z$ for the TM simulations.

the slab area. The dipoles are polarized in $y$ for TE mode excitation and in $z$ for TM mode excitation, as illustrated in figures 4.2a and 4.2b, where a single dipole is shown in each picture. There are also ten randomly distributed point time monitors (crosses in figure 4.2). The simulation volume has Perfectly Matched Layers (PML) in $z$ which absorbs light at the boundaries, resulting in insignificant reflections at the air-PML interfaces.

Two techniques are used to extract the mode frequencies from the time monitor data. The first technique is Lumerical’s built in “bandstructure” function which apodizes the time monitor data to exclude the dipole excitation pulse then applies a chirped $z$-transform, similar to a Fast Fourier Transform, to find the frequency components of the time data. The frequency domain data from each monitor is summed and the peaks in the spectrum are extracted. While this method is sometimes effective for finding the mode frequencies, the results are often plagued with extraneous data points due to issues arising from the finite nature of the calculation in time and space. An alternative approach is to use Harminv [21], a program that fits a finite number of decaying sinusoidals to a signal, outputting information...
Figure 4.3: 1D Bandstructure of TE (red) and TM (blue) modes of a 220nm thick silicon slab 1D grating suspended in air with $\Lambda = 795$nm and 300nm wide grooves. a) 1st Brillouin Zone b) Close up of band crossing (within the rectangle outlined in a)).

such as frequencies, quality factor, amplitude and decay constant. Imposing limitations on these parameters, it is possible to extract cleaner data than the previous method. Using a combination of these methods, the band structure shown in figure 4.3a is generated. However, neither method consistently finds mode frequencies near the band edges, where the group velocities are slow and the $Qs$ are high, because longer simulation times are required to resolve the modes. Another type of FDTD simulation is set up where, instead of using dipole excitation, a plane wave polarized in $y$ is incident from above, at small angles, and the light reflected off the surface of the structure is monitored in time. The time data is brought to the Fourier domain where Fano-like features appear at the mode frequencies [13]. The modes are extracted to complete the TE band structure calculation, as in figure 4.3b.

The TM modes lie at higher energy than the TE modes, as expected, because the untextured slab dispersion for TM modes is considerably higher than for TE modes ($\Delta f \approx 2250\text{cm}^{-1}$ for the lowest order modes at $\beta$ equivalent to 0.5 in figure 4.3). At the zone edge, $\beta = 0.5$, there is a large first order band gap in the TE band structure (3000-4000cm$^{-1}$), while there is almost no first order TM band gap (near 5500cm$^{-1}$). Thus, TM modes are free to propagate through the photonic crystal structure at frequencies within the TE band gap. The second order TE band gap (at zone centre, $\beta = 0$), lies below the second order TM bandgap, which is roughly half of the size. Near the zone centre, the “valence band”
edge of the TM modes (i.e. the lower band of the second order TM band gap) overlaps with
the “conduction band” edge of the TE modes (i.e. the upper band of the second order TE
band gap). This analysis therefore hints at the possibility for forward S/TE coupling, and
backward P/TM coupling.

While the dispersion of the actual 2D gratings studied in the rest of this thesis differs
quantitatively with these results, the main difference is just a reduction of all the energies,
while the near overlap of the TM valence and TE conduction bands remains.

The techniques described above can, in principle, be extended to 2D to find the band
structure of a rectangular lattice grating. However, the addition of the second direction
of periodicity complicates the band structure, making it more difficult to distinguish real
modes from artifacts. Since the band structure simulations of the infinite gratings also do
not yield coupling efficiencies and bandwidth estimates that can be compared directly with
experiment, no attempt was made to calculate the 2D band structure of the gratings used in
these experiments. In the next section, a comprehensive three-part simulation is described
that directly models the actual experimental behaviour.

### 4.2 Grating to Grating Transmission Simulations

In the experimental grating-to-grating measurements done in thesis, a beam incident on
a grating excites untextured slab modes which propagate in the slab until they reach a
second grating, that diffracts light off the chip to a detector. A simulation of this entire
structure requires a 250\(\mu\)m long span in \(x\), with feature sizes of 500nm and wavelengths of
1550nm. The small mesh required for convergence makes FDTD simulation of such a large
volume impractical. The grating-to-grating simulation is therefore broken into three parts:
in-coupling, propagation and out-coupling. These three types of simulations are described
in the following sections.
Table 4.1: Meshing parameters used for grating-to-grating FDTD simulations. Unprimed values are for the main simulation volume meshing, while the primed value is for the mesh refinement region. $\Delta x' = \Delta x$ and $\Delta y' = \Delta x$ and are omitted from the table.

<table>
<thead>
<tr>
<th>Mesh Parameter</th>
<th>Mesh Step (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$</td>
<td>39.75</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>37.5</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>22nm</td>
</tr>
<tr>
<td>$\Delta z'$</td>
<td>11nm</td>
</tr>
</tbody>
</table>

### 4.2.1 In-Coupling

Three dimensional FDTD simulations are used to simulate the coupling of light from free-space into the slab. The simulated structure is an SOI slab with a rectangular lattice of holes ($a_x = 795\text{nm}$, $a_y = 750\text{nm}$, $d_{hole} = 497\text{nm}$, with 25 and 29 periods in $x$ and $y$ respectively), like the device gratings described in chapter 3. A picture of the simulation volume as viewed from above (in the $x - y$ plane) is shown in figure 4.4a. We shall see in chapter 5 that both fibre and free-space excitation are used in experiments where the $1/e^2$ spot size diameters of light on the grating were close to 10$\mu$m and 20$\mu$m respectively. In each in-coupling simulation, a broadband Gaussian beam source is focused on the slab so that its waist, either 10$\mu$m or 20$\mu$m in diameter, is located at the grating. Simulations are done for different angles of incidence, and for S and P polarizations. Figures 4.4b and 4.4c show a $y - z$ view of the simulation volume for two different coupling geometries. In figure 4.4b, the beam is incident at 12° towards $+x$ and is S-polarized (the electric field is in the $y$ direction, parallel to the slab surface). In figure 4.4c, a P-polarized beam (the electric field is in the $x - z$ plane perpendicular to the slab surface), is incident at 25° towards $-x$.

The beam intensity profile at the source plane is shown (scaled arbitrarily) as well as a 2D frequency monitor (blue) in the $y - z$ plane that lies 15$\mu$m from the grating edge.

The simulation mesh details are summarized in table 4.1. To preserve the grating periodicities, the in-plane mesh steps ($\Delta x$ and $\Delta y$) are $1/20^{th}$ of the $a_x$ and $a_y$ lattice pitches respectively. A mesh refinement region, imposing $\Delta z' = 11\text{nm}$ ($1/20^{th}$ of the slab thickness), spans the volume around the slab.

Over the frequency range of interest ($6100\text{cm}^{-1}$ to $6600\text{cm}^{-1}$), S(P)-polarized light inci-
Figure 4.4: Schematics of the in-coupling simulation set-up. a) \(x - y\) view of the simulation area. The frequency field profile monitor is placed 15\(\mu\)m from the grating edge. b) \(x - z\) view of the simulation set-up used to for forward-coupling S-polarized light into the slab. The injected gaussian beam propagates the \(x - z\) plane, polarized in \(y\), with a 20\(\mu\)m spot on the sample (beam intensity at the injection plane is shown). c) Same as in a), but set-up for backward-coupling of P-polarized light.
Figure 4.5: In-coupling transmission spectra from FDTD simulations a) S-polarized excitation at 12° incidence (20µm spot, 6µm from edge) b) P-polarized excitation at 25° incidence (20µm spot, 8µm from edge). These are for a grating in air, with hole diameters of 497nm.

dent with the coupling geometry in figure 4.4b(4.4c), excites forward(backward) propagating TE(TM) modes which are detected by the monitor 15µm from the grating edge. The mode profiles at the monitor are discussed in the next section. For the rest of this chapter, the direction of coupling (forward or backward) are implied by the polarization (S or P) as the geometries described above are exclusively used.

Using the FDTD Solutions “transmission” analysis tool, the frequency dependent transmission of light through the monitor is calculated by,

$$T(f) = \frac{1}{2} \int \text{real}(P_{\text{mon}}(f)) \cdot dS_{\text{mon}} \cdot \frac{1}{2} \int \text{real}(P_{\text{source}}(f)) \cdot dS_{\text{source}}$$  (4.2)

where \(P_{\text{mon}}(f)\) is the frequency dependent Poynting vector measured by the monitor, \(dS_{\text{mon}}\) is the surface normal of the monitor. The denominator is the total power injected into a homogeneous material by an ideal source. The integral is an approximation due to the finite number of points in \(y\) and \(z\), however the appropriate meshing, including a region with refined meshing near the slab, is chosen for converged results. The transmission spectrum for an S-polarized beam injected at 12°, with a 20µm waist centered 6µm from the front edge of the grating, is plotted in figure 4.5a and the spectrum for a P-polarized beam injected at 25°, with the waist centered at 8µm from the front edge, is plotted in figure 4.5b.
Figure 4.6: Maximum coupling efficiency as a function of distance of the beam center from the edge of the grating for 20µm spots (circles/solid lines) and 10µm spots (triangles/dashed lines) for a) S-polarized excitation at 12° b) P-polarized excitation at 25°. These are for a grating in air, with hole diameters of 497nm.

Simulations are done with S and P-polarized light incident at 12° and 25°, respectively, on a grating with 10µm and 20µm spot diameters at different positions. The maximum coupling efficiencies are plotted in figures 4.6a and 4.6b respectively. The optimal beam positions for the 10µm spot centre are approximately 4µm and 6.5µm with respect to the output edge of the grating, for the 12° and 25° beams respectively, and were 5µm and 8µm for the 20µm spot. The optimal positions for the 25° beams are deeper into the grating than for the 12° beam, possibly in part due to its larger beam cross-section when projected on the grating surface. It is also possible that the excited TE grating mode (for 12°) diffracts out more quickly than the TM grating mode, causing the optimal coupling position to be closer to the grating edge. It is interesting to note that the coupling efficiencies are higher for the 10µm spot than the 20µm spot for the 12° beam but the opposite was true for the 25° beam. The maximum transmission efficiencies varied by less than 3% within 1µm of the optimal beam location. Beam position optimization was not done for every simulation geometry, as this analysis showed that deviations of ±1µm from the optimal position had little impact on the coupling efficiency.

For a given angle, the maximum coupling frequency is expected to be near the frequency of a grating mode with \( \beta = \frac{\omega}{c} \sin \theta \) in the first Brillouin zone. However, the maximum
coupling efficiency does not only depend on the coupling to the grating mode, but also the impedance-matching of the grating mode to the slab mode. The maximum coupling efficiencies are plotted against the in-coupling $\beta$ values in figure 4.7 where TE modes are in red and TM modes are in blue. These results, and those for in-coupling simulations done with a 2µm layer of photoresist (n=1.59) above the silicon, are compared to experimental results in section 6.4. In the next section, the mode profiles in the uncoated slab are investigated and the method used to propagate the mode to the second grating is described.

4.2.2 Propagation

The second step of the grating-to-grating transmission simulation is described in this section. In the design layout of the IMEC chips, adjacent gratings are separated by 195.33µm (edge to edge), as in figure 3.5a. The slab modes launched by S-polarized light are mostly TE as the fields are strongly polarized in the slab plane, with $\hat{z}$ oriented maximum intensities orders of magnitude lower. The modes excited by P-polarized light are similarly dominated by TM mode profiles. The $E_y$ intensity mode profile in the $y-z$ plane, at 15µm from the grating edge, due to excitation by S-polarized light (20µm spot) incident at 10°, is shown

Figure 4.7: Peak frequencies of power spectra measured by the slab monitor for TE (red) and TM (blue) in-coupling simulations. The peak frequency is plotted against the in-plane wavevector in the first Brillouin zone (main plot), found by $\beta = \frac{\omega_{\text{peak}}}{c} \sin \theta$. The inset shows the data plotted over a smaller range. These are for a grating in air, with hole diameters of 497nm.
in the right-most picture of figure 4.8a. The $E_z$ intensity profile of a mode generated by P-polarized light at $25^\circ$ is in the right-most picture of figure 4.8b.

Due to the finite area of the excitation spot, the fields launched into the slab adjacent to the grating couplers are amplitude modulated in the $\hat{y}$ direction, unlike the slab modes encountered in section 2.1 which propagated in $x$ and were uniform in $y$. As the modes in figure 4.8 appear to have this smooth single peaked variation in $z$, they are assumed to be made up almost entirely of the lowest order transverse ($n=0$ in chapter 2 terminology) TE and TM slab modes. To take into account the amplitude variation in the $\hat{y}$ direction, the field at the output of the grating coupler, inside the slab, is therefore expanded in a sum of $n=0$ slab modes propagating in different directions in the plane. Each $n=0$ mode propagates with a unique $\beta = k_x \hat{x} + k_y \hat{y}$, for a fixed $|\beta(\omega)|$ and has the form,

$$H_{\beta}^0(r) = f_{\beta}^0(z)e^{i\beta \cdot \rho} = f_{\beta}^0(z)e^{i(k_x x + k_y y)}$$ (4.3)

The total field in the $y-z$ plane at a position $x'$ is,

$$H_{\beta}^{\text{tot}}(x',y,z) = \sum_{k_y} C_{k_y} f_{\beta}^0(z) e^{i(k_x x' + k_y y)} = \sum_{k_y} C_{k_y} f_{\beta}^0(z) e^{i\sqrt{\beta^2 - k_y^2} x'} e^{ik_y y} dy$$ (4.4)

where $C_{k_y}$ is a complex factor that weights each $n=0$ mode contributing to the total field. Changing the sum to an integral and setting $\mathbf{F}(k_y) = C_{k_y} f_{\beta}^0(z) e^{i\sqrt{\beta^2 - k_y^2} x'}$, $H_{\beta}^{\text{tot}}(x',y,z)$ becomes,

$$H_{\beta}^{\text{tot}}(x',y,z) = \int_{-\infty}^{\infty} \mathbf{F}(k_y) e^{ik_y y}$$ (4.5)

This Fourier transform of $H_{\beta}^{\text{tot}}(x',y,z)$ yields the weighting factors, $\mathbf{F}(k_y)$, which decompose the total field into $n=0$ modes propagating with unique $k_y$ and $k_x$ values. These modes accumulate phase at different rates as they propagate, as determined by their $k_x$ values, causing the total field pattern to change as the wave propagates in the slab, from the input to the output grating. Finally note that this all assumes that subwavelength features in the field profiles at the output of the grating are associated with local fields that decay in $x$.

One method explored to propagate the fields a distance of 165.33 $\mu$m (195.33 $\mu$ (grating
Figure 4.8: Electric field intensity profiles in the $y-z$ plane for a) S-polarized excitation at $10^\circ$ ($E_y$ intensity plotted) b) P-polarized excitation at $19^\circ$ ($E_z$ intensity plotted). The left figures are profiles from FDTD grating simulations (15$\mu$m from grating edge), the middle are the approximate fields from MODE solutions and the right are the fields after propagating the approximate fields (middle) by 165.33$\mu$m. The intensities along $z = 0$ in c) and d) for the profiles in a) and b) respectively where red/black/blue lines are for left/middle/right plots.
separation)−15µm (in-coupling monitor position)−15µm (out-coupling source position, described in section 4.2.3), is to multiply each Fourier component by the phase associated with propagating a distance \( d \), \( e^{i\phi} = e^{i\sqrt{\beta_x^2-k_y^2}d} \), then inverse Fourier transform the result to get the final field as a function of \( y \). As the mode profiles are composed of discrete data points, Fast Fourier Transforms (FFTs) are used. This method did not prove to be effective as FFTs introduce large intrinsic phase errors due to spectral leakage [18].

Instead, the mode profiles at the \( y-z \) monitor, 15µm from the grating edge, are imported into MODE solutions for individual frequencies. The modes supported by a 220nm thick slab waveguide sitting on a SiO\(_2\) substrate with a width much wider than the mode profiles in \( x \) (90µm) are calculated at the imported mode frequency. The “propagate” function is used to calculate the power coupling of the imported mode to the waveguide modes and to propagate the waveguide modes (see section 2.5 or [33] for more detail). Anti-symmetric boundary conditions are applied for calculating TE modes while symmetric boundary conditions are applied for TM (see [32] for more details). The lowest and highest order modes used for TE and TM simulations are shown in figure 4.9. In this process, the imported field profile is approximated as a sum of waveguide modes at the same energy, but with discretely separated \( \beta_x \) and \( \beta_y \) values, with \( \beta(\omega)^2 = \beta_x(\omega)^2 + \beta_y(\omega)^2 \) fixed for a given \( \omega \). The profiles of the modes approximated for S-polarized light incident at 10° and P-polarized light incident at 19° are the center pictures of figures 4.8a and 4.8b. These fields have reasonably good agreement with the original fields. The approximated fields after propagating 165µm (195µm−15µm−15µm) are shown in the left most pictures of figures 4.8a and 4.8b. Cross sectional profiles (along \( z = 0 \)) are shown in 4.8c and 4.8d for the S and P excitation where the original mode is in red, the approximated mode in black and the propagated more in blue. Both the TE and TM propagated modes experience some broadening as is expected.

The propagated field profiles are found for S excitation at 10° and 12° and P excitation at 19° and 25°, for multiple in-coupling frequencies. To find the grating-to-grating coupling efficiencies, these propagated fields are imported back into FDTD and the out-coupling of light is simulated.
Figure 4.9: Profiles of waveguide modes used in the field propagation approximation. The waveguide is 90µm wide, substantially larger than the in-coupled fields (20µm wide). $E_y$ intensity profile is shown in a) for the first order TE mode, and in b) for the highest order TE mode used in the approximation. $E_z$ intensity profile is shown in c) for the first order TM mode, and in d) for the highest order TM mode used in the approximation.
4.2.3 Out-Coupling

The simulation set-up used for in-coupling is modified slightly for out-coupling. The $y-z$ monitor placed 15$\mu$m from the grating edge is replaced by an imported source, which is the propagated fields from MODE Solutions. An $x-y$ frequency monitor is placed 300nm above the surface of the grating and the Gaussian beam source is removed. An $x-z$ view of the out-coupling simulation is shown in figure 4.10. Examples of the field intensity collected at the monitor for TE and TM imported mode excitation are shown in figure 4.11. Light appears to diffract out of the TE mode more quickly than it does for the TM mode, as seen in figures 4.11a and 4.11b. The decay length of the TM mode appears to exceed the grating length in figure 4.11b. The profile of the injected TM field appears to have a width in $y$ slightly larger than the output grating width, causing light to diffract off the edges of the grating.

The fields detected at the monitor are projected into the far field (top half space) using Lumerical’s build in function “farfieldvector3d”. This function applies Fraunhofer diffraction equations [36] to evaluate the field on the surface of a half sphere with radius $R = 1m$. The far field intensity patterns on the half sphere, and the cross-section of the field intensity along the $y = 0$ axis, are shown in figures 4.12a and 4.12b, for a TE mode generated by S-polarized light at 10° incidence at its maximum in-coupling frequency, 191THz, and in figures 4.12c and 4.12d for a TM mode generated by P-polarized light at 19° incidence at its maximum
Figure 4.11: Examples of near field intensities 300nm off the surface of the grating for a) TE mode b) TM mode excitation found from FDTD simulations

in-coupling frequency, 192.33THz. The blue rings trace out far field angles separated by 10°, starting at 10°. From figures 4.12a and 4.12c, one can see that the out-coupling angles are very close to the in-coupling angles at the maximum in-coupling frequency. As predicted in sections 2.3 and 2.3.2, light is diffracted over a range of angles. Observing the far field profile along the x-axis, one can see ripples in the field intensity at the base of the peak which is a sign of sinc-like behaviour due the abrupt changes in the grating field amplitudes at the front grating/slab interface, as well as less abrupt changes at the rear interface where the grating mode decay length exceeds the length of the grating.

Away from the maximum in-coupling frequency, the modes diffract at angles different from the incident angle. In the transmission set-up described in section 5, light diffracted off the grating is collected by an elliptical mirror placed 15cm from the sample. The mirror is aligned so that its center lies directly on the path of light leaving the mirror at an angle equal to the input angle. Light diffracted from the grating away from this angle is not collected if it misses the elliptical mirror. This effect is shown in figures 4.13a and 4.13b where the far field intensities are plotted for different frequencies based on the same excitations that are used for figures 4.12a and 4.12c. The shape of the elliptical mirror projected onto the $R = 1$ m half sphere is outlined in each figure. The fraction of light captured by the elliptical mirror is estimated by summing the field intensities of points within the limits of the mirror. The
Figure 4.12: a) Example of a far field intensity plot for grating out-coupling of a TE mode generated by S-polarized light at 10° incidence at its maximum in-coupling intensity, 191THz. Blue rings trace far field angles separated by 10°, starting at 10°. b) Intensity of field in a) along $y = 0$. c) Far field intensity plot for grating out-coupling of a TM mode generated by P-polarized light at 19° incidence at its maximum in-coupling intensity, 192.33THz. d) Intensity of field in c) along $y = 0$. 
Figure 4.13: a) Far field intensity plots for f = 190THz, 191THz and 192THz for the same wave incident in figure 4.12a. The estimated collection area of the elliptical mirror is outlined in white. The fractions of light collected were 6%, 39% and 57%. b) Far field intensity plots for f = 188.33THz, 192.33THz and 195THz for the wave incident in figure 4.12c. The fractions of light collected were 20%, 64% and 54%. 

Overfilling fractions at 190THz, 191THz and 192THz for the S-polarized wave at 10° were 6%, 39% and 57% and the fraction at 188.33THz, 192.33THz and 195THz for the P-polarized wave at 19° were 20%, 64% and 54%. Unlike the results in figure 4.13b for fields generated by P-polarized excitation, the optimal filling occurs at a slightly different frequency than the maximum in-coupling frequency for the S-polarized excitation in figure 4.13b.

In both cases, the fraction of light collected is very sensitive to the alignment of the elliptical mirror. Experimentally, the uncertainty in the input and output alignment angles is ±0.5°. In this range, the overfilling factors at the in-coupling peak frequencies vary by ±5% and ±3% on average for TE and TM modes respectively.

The frequency dependent overfilling fraction is calculated for each out-coupling simulation. A summary of the grating-to-grating simulation results for the four coupling geometries studied is shown in figure 4.14. The in-coupling data (blue circles/lines) and out-coupling
Figure 4.14: Summary of FDTD simulation in-coupling results (blue circles/solid lines), out-coupling results with elliptical mirror overfilling (blue crosses/dash dot lines) and total grating-to-grating coupling results with frequency dependent elliptical mirror overfilling (red triangles) fit with Gaussians (solid black line). The left $y$ scale bar is the total transmission, while the right scale bar is for the other two spectra. The four plots correspond to: S-polarized excitation at 10° (upper left) and 12° (upper right), and P-polarized excitation at 19° (lower left), 25° (lower right).

The data with the elliptical mirror overfilling account for (blue crosses/dash dot lines) are plotted according the right $y$ (Transmission) scaling axis. The total transmission (red triangles), which is the product of the latter two, is plotted according to the left scaling axis. The total transmission data are fit with Gaussians to estimate the coupling properties such as the maximum transmission efficiency and FWHM. The fits results (black lines) are also shown in figure 4.14. While the P excitation fits appeared to follow the data more closely than the S excitation fits, in both cases, the fits were good enough to provide reasonable estimates of the properties of interest. These results are compared to experimental data in chapter 6.
Chapter 5

Transmission Set-up

In this section, the optical set-up that is used to measure the transmission of light from the input to the output grating couplers of the devices detailed in chapter 3, is described. Both the free-space and fibre excitation configurations are discussed. The alignment procedure is outlined and the power losses along the optical path are reported.

5.1 Layout

A previously designed and built transmission set-up was modified to accommodate a cryostat and to improve the focusing optics. A diagram of the modified transmission set-up is shown in figure 5.1. This set-up has the same basic layout as the previous one, and includes a custom designed outer rotation stage and elliptical mirror that were previously obtained. The transmission set-up is designed so that light generated by a Venturi TLB 6600 Swept-Wavelength Tunable Laser is incident on a grating coupler at an angle $\theta_1$ from the normal and is coupled into the patterned silicon chip. Light diffracted from another grating coupler at an angle $\theta_2$ from the normal is collected and sent to a detector. For the measurements discussed in this thesis, $\theta_1 = \theta_2$. This set-up is designed to accommodate a range of possible in-coupling and out-coupling angles. The outer rotation stage forms the base around which the rest of the experimental set-up is built. The excitation optics, which are described in detail in sections 5.2 and 5.3, sit on top of this rotating stage. The inner rotation stage,
which is aligned to be concentric with the outer stage, can independently rotate and translate vertically. On top of this stage are two orthogonal translation stages upon which the cryostat holder sits. Measurements in this thesis do not require temperature control or vacuum, so the outer shell of the cryostat is removed leaving the sample in air.

Both light diffracted from the grating coupler and scattered incident light are collected by an elliptical mirror. Light at one focal point of the mirror (the output grating) is imaged at the second focal point (the detector, either a CCD or a power meter). The sample image is magnified by a factor of 10. For alignment purposes, the elliptical mirror is attached to \( x, y \) and \( z \) translation stages as well as three tilt stages, allowing the mirror to rotate about three different axes. The ElectroPhysics Microviewer (Model 7290A) CCD camera displays an image of multiple devices on the chip when the excitation light is sufficiently defocused and
light scattering off the patterned silicon is sent to the camera. When the beam is focussed, the scattered light appears as a spot in the camera image. Light diffracted from a second grating also appears as a spot when there is sufficiently high transmission. An iris is placed in front of the camera so that the reflected input light is blocked, and light coupled out of the grating can be isolated. A Newport (818-G) detector is slid into place behind the iris for power measurements.

A Labview program and a National Instruments Data Acquisition (DAQ Model USB 6211) are used to communicate with the laser, and the Optical Power Meter (Model 1830C), connected to the detector. A schematic of these connections are shown in figure 5.2. Frequency sweeping parameters are sent from the Labview program to the laser via GPIB. For each measurement in this thesis, the sweep rate is set to 100nm/s and the data are averaged over 20 sweeps.

![Figure 5.2: Schematic of the electronic connections used for communication in the transmission set-up.](image)

**5.2 Free-Space Excitation Optics**

For free space excitation, the focusing optics are designed so that a Corning SMF-28 optical fibre with a normal angle cut is axially aligned with two identical plano-convex lenses held in a lens tube, as in figure 5.3. The first lens collimates the beam and the second focuses it on the sample. This one-to-one focusing system theoretically results in a spot on the focal plane the same size as the beam at the output of the fibre. The lens diameter was chosen to be 0.5 inches so that small coupling angles can be reached without blocking the light diffracted off the sample. To determine the required focal length of the lenses, the fibre output beam properties are studied. To estimate the divergence of the beam out of the fibre, a CCD
camera was used to measure the width of the beam at $1/e^2$ of its peak intensity. The $1/e^2$ half divergence angle, $\theta_{1/2}$, is 5 degrees. To avoid overfilling the first lens and to minimize the blockage of light by the second lens, lenses with 40mm focal lengths were chosen. Overfilling of the first lens undesirably results in lower transmitted power through the lens system as well as broadening of the beam shape at the focal plane. A measurement is taken to ensure that there was minimal overfilling of the first lens. The configuration in figure 5.3 is set-up without the polarizer and with the addition of an adjustable iris placed before the first lens and a detector replacing the sample at the focal plane. The power is measured for different aperture diameters and is plotted in figure 5.4. Note that the power doesn’t start to drop significantly until well past the lens diameter (1.27cm), indicating that overfilling is minimal. Assuming light propagates out of the fibre like a Gaussian beam, with its waist at the fibre output, the beam divergence angle, the beam diameter at the lens and the minimum beam diameter can be extracted from a fit of this data. The amount of power transmitted through an aperture with diameter $a$ placed a distance $l$ away from the waist of a Gaussian beam with diameter $d$ at the aperture is $A_0(1 - e^{-2a^2/d^2})$, where $A_0$ is the total power of the beam. For this geometry, $\theta_{1/2} \simeq d/l$ and the minimum beam diameter at the fibre, $d_0$, is $\frac{2\lambda}{\theta_{1/2}}$ [36]. The fit results yield a beam divergence of 5.1 ± 0.5 degrees and $d_0 = 11 \pm 1 \mu m$ $1/e^2$ which
Figure 5.4: Plot of the scaled beam power through different aperture sizes placed 3.8±0.2cm away from the fibre output. The diameter of the lens, 1.27cm is marked by a dashed line. The solid black line is the Gaussian fit of the data which yielded a $1/e^2$ beam diameter of 0.67cm±0.5cm at the first lens.

agrees well with the specified value, $d_0 = 10.4 \pm 0.8 \mu m$ at 1550nm [12].

While the beam diameter in the focal plane is predicted to be near 11$\mu$m for an ideal one to one imaging system, aberrations caused by the simple plano-convex lenses and small misalignments cause the diameter to be larger than this in reality.

The Knife-Edge Method is used to measure the minimum focused beam diameter [5]. This method, illustrated in figure 5.5, involves taking power measurements as a razor blade is incrementally moved across the beam perpendicular to the propagation axis. For a Gaussian beam, the results can be fit by the following function to extract the diameter, $d$, of a beam centered at $x_0$ at a position along the z propagation axis [5],

$$P(x) = \frac{1}{1 + \exp(c_0 + c_1 X + c_2 X^2 + c_3 X^3)} \quad (5.1)$$

where $X = \frac{4}{d}(x - x_0)$, $c_0 = 6.71 \times 10^{-3}$, $c_1 = 1.55$, $c_2 = 5.13 \times 10^{-2}$ and $c_3 = 5.49 \times 10^{-2}$.

Measurements are taken at different locations along the axis and, by this Gaussian beam model, the diameter varies with position along the axis $z$ like $d = d_m \sqrt{1 + \frac{4z^2}{\pi d_m^2}}$.

The knife edge results for horizontal ($x$) and vertical ($y$) sweeps at the minimum diameter
Figure 5.5: Schematic of the Knife Edge Method. The upper box shows the razor blade sweeping through the beam for horizontal and vertical measurements. In the lower box, the vertical lines show slices along which measurements were taken for different positions along the optical axis. The red lines indicate the width of the beam as it propagates.

positions are shown in figures 5.6a and 5.6b. The power is scaled to 1 where the knife is well away from the beam. The beam appears to be symmetric and deviates from Gaussian behaviour away from the center. This is likely due to abberations associated with the relatively simple lenses. The solid circle data points are included in the fit (black line). The widths at different locations along the axis are plotted in figures 5.6c and 5.6d. The fit of the widths for the horizontal sweeps (black line in 5.6c) do not agree within the uncertainty of the all the diameters and yield a minimum diameter $15\pm2\,\mu m$. The horizontal and vertical minimum diameters found by (5.1) are $16.2\pm0.6\,\mu m$ and $23.5\pm0.4\,\mu m$, where the uncertainty is from the the 90% confidence interval of the individual fits. This uncertainty is larger in reality due to the non-Gaussian nature of the beam and roughness in the knife edge.

This non-Gaussian behaviour and large spot sizes are problematic for grating coupling, where incident light is only coupling into the slab if it is incident on the $20\mu m$ by $20\mu m$ grating region. To estimate the power distribution of the focussed beam, the power transmitted
Figure 5.6: Knife Edge Method measurement results. Horizontal and vertical sweep data at the minimum $1/e^2$ beam diameters $16.2 \pm 0.6 \, \mu\text{m}$ and $23.5 \pm 0.4 \, \mu\text{m}$ are shown in a) and b). The solid circles are used to fit the data (black line). The beam widths extracted from fits of horizontal and vertical measurements made at different positions along the optical axis are shown in c) and d). Errorbars show the 90% confidence interval uncertainty. The black line in c) is a Gaussian beam fit of the data. The absolute positioning in all plots is arbitrary.
through three different pinholes (10\(\mu\)m, 25\(\mu\)m and 50\(\mu\)m in diameter) placed at the beam center is measured. The experimental set-up is illustrated in figure 5.7 and the transmitted powers are plotted in figure 5.8. The detector was placed at the focal plane to measure the reference power used to scale the data. Approximately 65\% of the power incident on the 25\(\mu\)m pinhole is transmitted, compared to 96\% for an ideal Gaussian beam with a 20\(\mu\)m diameter. This effect of the poor quality spot on grating coupling efficiency is discussed further in chapter 5.

Figure 5.7: Schematic of the optical set-up used to measure the transmission of light through pinholes placed at the focal plane of the two lens system, used in the transmission set-up, that collimates then focusses light from a fibre. Light transmitted through the pinhole is focused onto a detector by a third lens.

Figure 5.8: Transmission of light through pinholes (red markers) 10, 25 and 50\(\mu\)m in diameter, placed at the focal plane of the two lens system, used in the transmission set-up, that collimates then focusses light from a fibre. The pinhole diameters have \(\pm 5\%\) uncertainty. The transmission is also plotted for an ideal 20\(\mu\)m Gaussian beam incident on the pinholes (black line).

The fiber holder sits on a translation stage, which is fastened to a plate that also holds the two lenses, so that the three elements are on a common optical axis. This plate sits on three translation stages. To adjust the focus on the sample, one stage is used to translate the input optics towards sample. To place the beam at the appropriate location on the sample,
a vertical translation stage is used as well as one that translates tangentially to the circular rotation stage. The input polarizer is designed for the 0.5 inch lens tubing system and is attached after the second lens.

As part of a transmission efficiency measurement, the input power spectrum is measured. For free-space measurements this was done by adding a mirror after the tubing system such that the light is focused on the detector, as shown in figure 5.9.

![Figure 5.9: Layout of the optics used to measure the power incident on the sample in free-space transmission measurements.](image)

### 5.3 Fibre Excitation Optics

Transmission measurements are also taken with fibre excitation, where a normal cut fibre is placed a small distance off the surface of a grating coupler. The input optics described above are modified by removing the lens tube and aligning a fibre holder along its axis. The fibre holder is directly attached to the three translation stages and is adjusted in the same way as described above. In this case, the minimum excitation spot on the sample is achieved by bringing the fibre as close as possible to the sample. This must to be done very carefully because if the fibre touches the sample, both can be damaged. While a polarizer can’t be placed before the sample, the light ejected from the fibre is reasonably well polarized, with
approximately 93± 2% of the power in one polarization.

Input power reference measurements are taken by translating the sample away from the fibre making room for a power meter. The power meter is rotated slightly off the fibre axis normal to avoid back-reflections into the fibre that can potentially damage the laser.

5.4 Alignment

As with any multi-component optical system, the quality of measurement results depend strongly on the alignment of the system. The alignment procedure followed to successfully integrate each component is described in this section. The majority of the alignment of the system is done with the free-space excitation optics, in figure 5.3, but with the fibre output replaced by a white light source illuminating a 100μm pinhole.

5.4.0.1 Rotation Stages

The first step is to align the source so that light travels radially towards the center of the rotation stage. This is done by using two alignment tools, shown in figure 5.10, that were previously designed and built in this lab. Alignment Tool 1 attaches to the unrotating outside of outer stage and suspends a plate marked with the center of the rotation stage. Alignment Tool 2 marks the center of the hole that it sits on. The white light source is adjusted so focused light hits the center marker of Tool 1 over a range of rotation angles. Tool 1 is then removed and Tool 2 is placed on the far side of the rotation stage radially across from the source. The second lens is removed so that light is focused on Tool 2. The source is adjusted to hit the center marker of this tool. Small adjustments are made until light goes through both center markers.

The inner rotation stage then has to be axially aligned with the outer stage. Tool 2 is placed at the center of the inner rotation stage. The inner stage is adjusted relative to the outer stage until the beam hits the middle of Tool 2 for different inner and outer rotation stage angles.
5.4.1 Elliptical Mirror

The elliptical mirror is placed 15cm away from the center of the rotation stages aligned with the 0 degrees marking on the outer rotation stage. Mirror 1 and the CCD camera are positioned so that light reflected off the elliptical mirror travels 150cm to reach the camera. Before the elliptical mirror can be aligned, the height of the optical plane has to be chosen. The cryostat holder with the sample in place is mounted on the two translation stages sitting on the inner rotation stage. A level collimated HeNe laser is used to ensure that the sample, the elliptical mirror, the detector, the CCD camera and the source are at the same height. It is also used to ensure the source is level and Mirror 1 has no vertical tilt. To align the tilt of Mirror 1 about its vertical axis, a temporary mirror is placed on the path between the elliptical mirror and Mirror 1. The HeNe laser is aligned to hit the temporary mirror and send light along this path. The tilt of Mirror 1 is adjusted until light is collected by the camera.

The sample is then translated roughly to the center axis of the rotation stages. This is done by moving the cryostat holder until the light appears to be focussed on the sample at the same location for different inner and outer stage rotations. The sample is then rotated to an angle $\theta$ and the outer rotation stage to an angle $2\theta$ so that light reflected off the sample
and goes to the elliptical mirror (as in figure 5.1 with $\theta_1 = \theta_2$). The position of the elliptical mirror is adjusted so that center of the beam reflected off the sample falls at the center of the elliptical mirror. The three translation and tilt directions are shown in figure 5.11. The tilt of the elliptical mirror about Axes 1 and 2 are adjusted so that light reflected off at the same level. The tilt about the Axis 3 is adjusted so that light reflected off the mirror at approximately 90 degrees.

![Diagram showing rotation and translation axes](image)

**Figure 5.11:** The elliptical mirror, as seen from above, with thick red arrows indicating the direction of light propagation. The three rotation axis of the tilting stages are shown as well as the three translation directions.

At this point, a skewed spot appears on the CCD camera and the shape of the beam changes greatly along the optical path. Two types of adjustments are made to fix this problem. The mirror is rotated about its Axis 3 and then translated laterally to offset the change in the beam direction. Likewise, the tilt about Axis 2 is adjusted and the mirror is translated vertically. Once the beam shape remains fairly constant (although varying in size due to focusing), the CCD camera is used for final adjustments.

The sample is positioned so that the beam hits the patterned area of the chip. The beam is defocused off the sample so that light scatters off the devices and an image of them is projected on the CCD camera. Final adjustments are then made to the elliptical mirror to obtain a crisp image. The focus of the elliptical mirror is adjusted until the devices can be recognized. The positioning of the sample is then fine-tuned so that the devices appear to
remain in the same position when the inner stage is rotated. Opposing tilt and translation adjustments are then made to improve the image.

Once the alignment is satisfactory, the white light source and pinhole are replaced with the infrared laser fibre output. Final adjustments are then made and the elliptical mirror is left untouched during measurements.

5.4.2 Angle Alignment

With the optical components aligned, the rotation angles of the inner and outer stages can be set. The angle of the outer stage is set using alignment markers on the stage. For the inner stage, the $\theta = 0$ angle is estimated and the stage markers can be used for relative angle rotations. To refine the inner stage angle, the beam is defocused and the stage is slowly rotated back and forth. On the CCD camera it is possible to see when the light reflected off the sample is optimally collected by the elliptical mirror. Measurement can be taken for incident angles ranging from 9 degrees to over 30 degrees.

5.5 Reflectance and Transmittance of Optical Components

To find the transmission efficiency of a device, the power must be measured directly before entering and leaving the device. For this transmission set-up, light reflects off mirrors and travels through polarizers before reaching the detector. To take these power reductions into account, measurements are taken to find the reflectance of the mirrors and transmittance of the output polarizer. To calculate reflectance and transmittance, the power spectra are found with and without each optical component in the optical path. The measurements are taken for both incident polarizations ($S$ and $P$), and the set-ups used are shown in figure 5.12. Table 5.5 summarizes which set-ups are used for each comparison. As measurements are done in pairs for each calculation, multiple measurements are taken with set-ups appearing more than once in table 5.5. The spectra are smoothed over the frequency range measured.
Table 5.1: Summary of the optical set-ups used to calculate the reflectance and transmittance for each component. The set-ups used to measure the power with and without each component in the optical path are illustrated in figure 5.12 and numerically labelled 1 through 4.

<table>
<thead>
<tr>
<th>Component</th>
<th>With</th>
<th>Without</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror 1 + Elliptical Mirror</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Mirror 2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Polarizer</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

(1520-1630nm) so that the Fabry-Perot oscillations due to multiple reflections are filtered out. The results are summarized in table 5.2 where the maximum, minimum and mean values of the filtered data for this frequency range are given for each optical component (see figures 5.1 and 5.9 for labelled diagrams).

5.6 Overfilling of the Elliptical Mirror

For the transmission measurements discussed in this thesis, light diffracted out of a grating coupler is collected by the elliptical mirror (as shown in figure 5.1). Light is found to diffract out of the grating coupler such that the elliptical mirror is overfilled, even at the peak
<table>
<thead>
<tr>
<th>Optical Component</th>
<th>Mean (%)</th>
<th>Min (%)</th>
<th>Max (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror 1 + Elliptical Mirror $S$</td>
<td>86.4</td>
<td>85.7</td>
<td>87.5</td>
</tr>
<tr>
<td>Mirror 1 + Elliptical Mirror $P$</td>
<td>83.3</td>
<td>83.2</td>
<td>83.5</td>
</tr>
<tr>
<td>Mirror 2 $S$</td>
<td>92.2</td>
<td>91.2</td>
<td>92.7</td>
</tr>
<tr>
<td>Mirror 2 $P$</td>
<td>94.8</td>
<td>94.5</td>
<td>95.1</td>
</tr>
<tr>
<td>Polarizer $S$</td>
<td>52.9</td>
<td>52.5</td>
<td>53.4</td>
</tr>
<tr>
<td>Polarizer $P$</td>
<td>52.3</td>
<td>51.8</td>
<td>52.3</td>
</tr>
</tbody>
</table>

Table 5.2: The reflectance of the mirrors and transmittance of the polarizers for $S$ and $P$ polarized light for $\lambda = 1520\text{nm}$ to $1630\text{nm}$.

coupling frequency, as discussed in chapter 4. To measure the fraction of light diffracted out of the grating that is collected by the elliptical mirror (and is subsequently sent to the detector), light diffracted from a grating coupler is measured before and after the elliptical mirror. An appropriate coupling angle is chosen so the grating coupler peak frequency is aligned with the resonance frequency of the device microcavity, when excited directly by a fibre. This measurement was done on R4C5s6 (on a chip from the 8th column of the wafer) with $11^\circ$ incident light. A thin piece of plastic is carefully placed to block the unwanted reflected input light that would otherwise reach the elliptical mirror. Fibre excitation is used instead of free-space excitation to minimize stray reflected light. To measure the power spectrum before the elliptical mirror, the two lenses from free-space set-up are used to focus light off the sample into the detector as illustrated in figure 5.13. The power spectrum after the elliptical mirror is measured using Mirror 1 and the detector in their normal configuration (see figure 5.1) without the output polarizer. In comparing the spectra, the reflectance and transmittance of optical elements that were not common to both measurements were taken into account. The transmittance of the two lenses is measured to be 82%, which is close to what one would expect for four air-glass interfaces ($0.96^4 = 0.849$). A comparison of the two spectra after subtracting off background light is shown in figure 5.14. Approximately 47% of light out the grating coupler is collected by the elliptical mirror. This compares reasonably well with the maximum filling transmission fractions, 57 % and 61%, found in simulations for $10^\circ$ and $12^\circ$ incidence respectively, as discussed in chapter 4.
Figure 5.13: Layout of set-up used to measure the light out of a grating before the elliptical mirror as part of the overfilling calculation. The red lines are used to indicate beams of light. Divergent light reflected from the sample is blocked by a piece of plastic and light out the grating coupler is collected by the lenses and measured by the detector.

Figure 5.14: Comparison of power spectra before (blue) and after (red) the elliptical mirror when a device is resonantly excited and light leaving the grating is collected and reflected incident light is blocked. The background in both is spectra due to stray reflected light has been subtracted.
Chapter 6

Grating Characterization

In this section, experimental results are reported for transmission measurements taken with
the set-up described in chapter 5, where light focused on one grating, propagates through
the slab, and is diffracted out by an adjacent grating. Measurements are taken over a range
of incidence angles for gratings couplers with different holes sizes and surface coverages. The
results are compared with the simulation results of chapter 4, and the literature, in section
6.5.

6.1 S and P Coupling Geometries

The grating-to-grating coupling geometries are shown in figure 2.1 (in chapter 2). For the
measurements described in this section, grating-to-grating coupling experiments are done
with polarizers at both the input and the output, as shown in figure 2.3. For the devices
tested, S-polarized light incident on a grating at frequencies within the laser tuning range
couples to forward propagating modes and P-polarized light couples to backwards propagat-
ing modes, as is also found in simulations described in chapter 4.

For the coupling geometry in figure 2.3, S-polarized light couples to TE slab modes as it
has no electric field component normal to the slab. The P-polarized light has electric field
components both normal to the slab and parallel to the slab as shown in figure 2.3b. As the
parallel component is not in a TE orientation, and as predicted by simulations in chapter 4,
the P-polarized excitation must couple to TM slab modes. This was verified by modifying
the transmission set-up so that light is collected from the edge of the chip. First, the coupling
spectrum for P-polarized light back-coupled into a grating in the 5th column of devices and
out the adjacent grating in the last column is measured. Then, P-polarized light is focused,
at the same angle, on the grating located closest to the edge of the chip, in the same row.
When the back-coupled light transmitted out the edge of the chip is sent through a polarizer
aligned normal to the slab surface, and is then focussed onto a detector, as illustrated in
figure 6.1, a large signal is observed. When the output polarizer is oriented in the plane
of the slab (so it would transmit light escaping via TE modes), the signal was negligible,
thus confirming that P-polarized excitation of the gratings excites backward propagating
TM modes in the slab.

One would expect the shape of the grating-to-grating coupling spectrum to be the same
as the square of the grating-to-edge spectrum because the former passes through two gratings
and the latter only one. This is verified in the upper plot of figure 6.2 where the grating-
to-grating transmission (blue) is compared to the grating-to-edge transmission (red) for the
geometry in figure 6.1. The two spectra are scaled and offset by different factors.

Figure 6.1: Coupling geometry used to measure light out the edge of the chip for P-polarized
excitation.
Figure 6.2: Top: Comparison of the spectral shape for the grating-to-grating transmission (blue) and grating-to-edge (red) squared transmission with the output polarizer is oriented in the direction of TM modes, as in figure 6.1. The spectra are scaled and offset by different arbitrary constants. The correlation in these two spectra indicates that P polarized light backouples to slab TM modes. Bottom: The grating-to-edge squared transmission (arbitrarily scaled) with the output polarizer in figure 6.1 oriented in the direction of TE modes. There is little evidence of the grating-to-grating coupling peak indicating that an insignificant amount of P polarized light is backcoupled in to TE modes.

6.2 Coupling Measurement Procedure

The spectra reported in this section correspond to the absolute transmission efficiency of light from directly before the input grating to directly after the elliptical mirror, as obtained using the following multi-step process. The absolute power after the elliptical mirror, and the input power just before the input grating are corrected to take into account measured reflectivities of mirrors and the transmission of the polarizers. Overfilling of the elliptical collection mirror is not corrected for in the data presented in this section, unless stated. The coupling efficiency spectrum is calculated by first removing the background noise in the grating-to-grating spectrum (i.e. setting the power away from the coupling peak to 0) then dividing this by the input spectrum.

The angles of the sample and the inner and outer rotation stages are set following the steps outlined in section 5.4.2. The uncertainty in the measurement angle is ±0.5 degrees. A preliminary measurement is done to roughly identify the optimum coupling frequency,
by tuning the laser, focussed on an input grating, while imaging the corresponding output grating. The laser is then set to this frequency to optimize the focus and placement of the beam. Using the laser focussing lenses, the laser spot on the sample surface is first made large enough so that light diffracting from more than one adjacent grating can be observed on the CCD camera. The spot size is then reduced so that as the beam position is adjusted vertically from grating to grating (s1 to s6), light transmitted out the adjacent gratings is minimized when the input beam is between gratings. The tightly focused spot is then placed over top of the desired input grating and fine adjustments are made so that the light coupled out of the corresponding output grating is maximized. The aperture is then closed so that all out-coupled light is passed and background light (scattered incident light) is minimized. The camera is then removed and replaced by the detector, which is finely adjusted to maximize the signal strength.

Measurement reproducibility is tested for both S and P polarized light incident on device R4C5s6 (chip A6), covered with resist. In both cases, the procedure described above is followed start to finish and appears to yield consist results (as demonstrated in figure 6.3).

Figure 6.3: Grating-to-grating coupling spectra for multiple measurements of device R4C5s6 (chip A6) covered with resist for 10 degrees angle of incidence. a)Four trials (red, blue, green, black) for S-coupling b) Three trials (red, blue, black) for P-coupling
6.3 Experimental Grating Characterization Results

The coupling efficiency spectra are compared for different resist-coated devices on chip A6, and the results are shown in figure 6.4. While there are small variations in the width and amplitudes of the peaks, the peak frequencies vary minimally. The latter finding is important because if this were not the case, coupling into and out of the devices would require different angles and this would add a level of complexity to the measurements.

The coupling spectra are also compared for two devices on chips that are from a different row but the same column on the wafer, as shown in figure 6.5 where E8 and F8 results are compared. These spectra have similar lineshapes, as is expected because the deep UV exposure dose is set to be the same along a given column, resulting in nominally the same sized holes.

The grating-to-grating coupling spectra of four different devices are measured over a range of incidence angles. The four devices have grating hole sizes \( h = 548\text{nm}, 541\text{nm}, 528\text{nm} \) and \( 497\text{nm} \). While measurements are taken on all of the devices coated with resist, the last device is also measured uncoated. Gaussian curve fits are used to analyze features of interest. Parameters \( a \) and \( b \) in the fit function, \( G(f) \), correspond to peak frequency and maximum coupling efficiency while \( 2\sqrt{2\ln 2}c \) corresponds to the full width at half maximum.
Figure 6.5: Comparison of the coupling spectra for devices on chips E8 (blue) and F8 (red) for 10 degrees angles of incidence. The spectra are scaled by different arbitrary constants (FWHM).

\[
G(f) = ae^{-\frac{(f-b)^2}{2c^2}}
\]  

(6.1)

These fits generally agree well with the data. The coupling efficiencies with Gaussian fits for S and P light incident at different angles for the \( h = 548 \text{nm} \) device are shown in figure 6.6. The coupling efficiencies and peak frequencies increase with coupling angle for S excitation and decrease for P excitation.

Figure 6.6: Angle tuning of grating-to-grating coupling spectra for a resist-coated grating with \( h = 548 \text{nm} \). Angles of incidence for a) S-coupling: 10, 11, 13, 15 degrees (left to right) b) P-coupling: 11, 12, 13, 14, 15 degrees (right to left)
6.3.1 Band Structure Results

The grating coupler band structures are inferred by plotting $\beta = \frac{\omega}{c} \sin \theta$ against the peak frequency for each sample. The band structure for the resist coated sample with $h = 548$nm is plotted in figure 6.7. Note that the slope is positive for S coupling (red) and negative for P coupling (blue), as one would expect for forward and backwards propagating modes. The bands appear to flatten out near the band edge, as is characteristic of grating bands. The error bars in $\beta$ result from the uncertainty in the angle of incidence. The uncertainty in the peak frequencies due to variability in measurements (as discussed in section 6.2) and the Gaussian fits are omitted from the following figures as they are too small to provide further information on the device behaviour. The TE (S) and TM (P) bands are plotted separately in figures 6.8a and 6.8b for the four resist-coated samples.

![Figure 6.7: Band diagram for a resist-coated grating with $h = 548$nm generated from coupling spectrum measurements at different angles of incidence. The peak frequency values are extracted from Gaussian fits of the coupling spectra. Red and blue markers indicate S-coupling and P-coupling. The horizontal line provides a reference to observe band flattening.](image)

The band structures for the $h = 497$nm device with and without a resist coating are plotted in figure 6.9. The TE band is approximately $400 \text{cm}^{-1}$ higher in energy for air (red triangles) than for resist (red circles) while the energy difference between TM air (blue triangles) and resist (blue circles) bands is even greater (although more data would be required to make an estimate).
Figure 6.8: Band structure measurement results for resist coated samples with holes sizes 548nm (○), 541nm (△), 528nm (+), 497nm (∗) for a) S-coupling b) P-coupling

### 6.3.2 Maximum Coupling Efficiency and Bandwidths

The maximum coupling efficiencies and full width at half maximum (FWHM) of the coupling spectra at a given angle of incidence, for all devices measured, are plotted in figures 6.10a and 6.10b. The vertical error bars due to measurement variability and goodness-of-fit are again omitted as they are too small to contribute additional information about trends in the data. As already noted, the maximum coupling efficiency for TE coupling generally increases with $\beta$ while for TM it generally decreases. The same trends apply for the FWHM. There are points in both plots that deviate from this trend (outside the uncertainty).

Another quantity that is commonly plotted is the integrated power. This is the total spectral power for a given angle of incidence and corresponds to the area under the coupling power spectrum. Integrating the Gaussian in (6.1) over all frequencies yields an integrated power $ac\sqrt{2\pi}$, which is proportional to the maximum coupling efficiency times the FWHM. The integrated power scaled by a constant is plotted in figure 6.10c. Compared to figures 6.10a and 6.10b, the variations in figure 6.10c are smoother. The integrated power for TE coupling increases with $\beta$, whereas for TM coupling it decreases.
6.4 Comparison to Simulation Results

The structure in the simulations described in chapter 4 is designed to have the same features as the device that is measured in air and resist, with holes diameters measured to be approximately 497nm. In this section, the simulated and experimental peak frequencies, coupling efficiencies and bandwidths are compared for grating couplers on chip D13, without a photoresist coating. The simulated in-coupling peak frequencies are compared to the peak frequencies found experimentally for photoresist coated grating couplers.

6.4.1 Angle Tuning of Maximally Coupled Frequency

The experimental and simulation peak coupling frequencies for the uncoated grating couplers are plotted against the in-coupling $\beta$ values the extended zone scheme in figure 6.4.1. The simulated in-coupling peak frequencies for TE and TM modes (red and blue empty triangles) are moderately close to the grating-to-grating peak frequencies (red and blue filled triangles), which are found from fits of the spectra, shown in figure 4.14, resulting from the product of three contributions: i) in-coupling efficiencies, ii) the out-coupling efficiencies and iii) the frequency dependent elliptical mirror overfilling factors. The TE and TM experimental peak frequencies (red and blue circles) lie at higher energy than the simulated data ($\Delta f \simeq$...
Figure 6.10: Features of interest extracted from coupling spectra for coupling measurements of resist-coated samples with $h = 548\text{nm}$ ($\circ$), $541\text{nm}$ ($\triangle$), $528\text{nm}$ (+), $497\text{nm}$ ($\ast$) and bare sample ($\times$) with $h = 497\text{nm}$. Plotted are a) Maximum Coupling Efficiency b) FWHM c) FWHM multiplied by Maximum Coupling Efficiency. S-coupling and P-coupling results are in red and blue respectively.
Figure 6.11: TE (red) and TM (blue) band structures for in-coupling simulation results (empty triangles), total grating-to-grating simulation fit results (filled triangles) and experimental results (open circles) for a grating with $h = 497\text{nm}$ plotted in the extended zone scheme. Dispersion, found analytically in section 2.1, of the lowest order TE (red line) and TM (blue line) untextured modes are plotted as well as the substrate light-line. Lines adjacent to the dispersion curves show the slope of TE and TM experimental data for comparisons of band curvatures.

200cm$^{-1}$ for TE, 140cm$^{-1}$ for TM) but follow approximately the same trend. The substrate light line (black line) and the dispersion of the lowest-order TE and TM untextured SOI slab modes (red and blue lines) are also plotted in figure 6.4.1.

The peak coupling frequencies for gratings with and without a resist coating are plotted in figure 6.4.1. The experimental (circles) and in-coupling simulation (triangles) data are plotted for TE and TM bare grating results (red and blue respectively) and the TE and TM resist coated grating results (magenta and cyan respectively). There is better agreement of simulation and experimental results for the resist coated gratings ($\Delta f \simeq 65\text{cm}^{-1}$ for TE, 30cm$^{-1}$ for TM) than for the bare gratings.

6.4.2 Absolute Coupling Efficiencies, Bandwidths and Integrated Power

The simulated grating-to-grating transmission peak values, extracted from the fits in figure 4.14, are plotted with the experimental maximum transmission results in figure 6.13. The TE simulation results (red triangles) agree much better with the TM experimental results
(red circles) than do the TM simulation results (blue triangles) with the TM experimental results (blue circles).

The FWHM results for the simulation and experimental data are plotted in figure 6.14, with the same markers used as in figure 6.13. The simulation data again includes the frequency dependent overfilling of the elliptical mirror. In this case, the FWHM of the TE and TM data sets agree reasonably well. The integrated power, estimated as the FWHM multiplied by the maximum coupling efficiency, is plotted in figure 6.4.2, for grating-to-grating experimental and simulation results as described above. The TE data sets appear to agree reasonably well while the TM simulation data points are at much higher integrated power than the TM experimental results.

6.5 Discussion

6.5.1 Impedance Matching of Grating and Untextured Slab Modes

The preceding comparisons directly show that the simulations are consistent with the experimental determination that the backward coupled P-polarized light excites TM polarized slab
Figure 6.13: Grating-to-grating maximum coupling efficiencies extracted from Gaussian fits of the experimental data (circles) and the simulation data accounting for frequency dependent elliptical mirror overfilling (triangles), for \( h = 497 \text{nm} \), bare gratings. TE and TM results are blue and red respectively.

modes, while S-polarized, forward coupling is via TE slab modes. Thus the grating “band structure” extracted as described above for S and P polarized excitation can be attributed directly with TE and TM polarized grating modes. Figure 6.4.1 shows that the TM band structure associated with the grating modes lies closer to the TM untextured slab mode dispersion than the TE grating band does to the TE untextured slab mode dispersion. One would expect that this should result in stronger TM coupling, than TE coupling, of grating modes to slab modes, based on the effect of “impedance mismatching” on the reflection of grating modes at the slab/grating boundary, as discussed in chapter 2. This effect appears in figure 6.10a and 6.13 where the TM modes reach higher overall coupling efficiencies, both in experiment and in simulations.

The impedance mismatching between grating and slab modes varies with \( \beta \), as can be observed by comparing the relative curvatures of the grating and untextured slab bands in figure 6.4.1. The line near the uniform slab TE dispersion curve helps show that the TE grating band has a shallower slope than the untextured slab band, causing the bands to be closer at higher \( \beta \), decreasing the effective index mismatch. This \( \beta \) dependence is consistent with simulation and experimental results in figure 6.13, where the general trend is for TE
coupling efficiencies to increase with $\beta$. In figure 6.4.1, the TM band has a steeper slope than the untextured slab band, and the effective index mismatch increases for large $\beta$ in the extended zone scheme. In the first Brillouin zone, the TM effective index mismatch decreases for large $\beta$. In figure 6.13, the experimental TM coupling efficiencies decrease with increasing $\beta$ (in the first BZ) while the simulated TM coupling efficiencies increase. The latter is consistent with predicted impedance mismatching effects, while the former is inconsistent, indicating that there are potentially other $\beta$ dependent effects that dominate.

### 6.5.2 Comparison of Experimental and Simulation Absolute Maximum Coupling Efficiency Results

The simulated and experimental absolute maximum coupling efficiencies are plotted in figure 6.13, where data corresponding to transmission from directly before the input grating to directly after the elliptical mirror is plotted. The simulation data (triangles) are calculated using in-coupling and out-coupling efficiencies, in addition to frequency dependent elliptical mirror overfilling factors. The experimental data (circles) have no correction factors (aside from those taken into account in every measurement, i.e. mirror reflectivities and polarizer transmissions). Both the TE and TM simulated maximum coupling efficiencies lie at higher
6.5.2.1 Experimental Efficiency Reduction due to Beam Quality

In section 5.2, characterization of the free-space incident beam reveals that the spot shape at the focus is non-Gaussian, and approximately only 65\% of the total power is transmitted through a 25\(\mu\text{m}\) pinhole. This leaves at least 35\% of incident light outside of the in-coupling grating region (20\(\mu\text{m}\) by 20\(\mu\text{m}\)). However, in simulations, an “ideal” 20\(\mu\text{m}\) diameter Gaussian beam spot is incident on the grating, which has 96\% of incident light within a 12.5\(\mu\text{m}\) radial distance of the beam center.

To roughly estimate the experimental grating-to-grating transmission of light that is actually incident on the input grating, the experimental data from figure 6.13 is divided by 0.65 and is plotted with the grating-to-grating simulation data divided by 0.96 for consistency, in figure 6.16. The scaled experimental TE transmission efficiencies in figure 6.16, are 1.8\% and 2.3\% for S-polarized excitation at 10\(^\circ\) and 12\(^\circ\) respectively, and compare well to the scaled simulated efficiencies, 1.9\(\pm\)0.3\% and 2.5\(\pm\)0.3\% (uncertainty from 95\% confidence bounds from the Gaussian fit). The scaled maximum TM experimental efficiencies, 7.3\% and 5.5\% for 19\(^\circ\) and 25\(^\circ\) incidence, respectively, are still roughly half those found by simulations. Further simulations and analysis are required to better understand the discrepancies in the simulated and experimental TM coupling efficiencies.
Figure 6.16: Grating-to-grating maximum coupling efficiencies of light incident within the grating region for experimental results (circles) and simulation results (triangles), for $h = 497\text{nm}$, bare gratings. The estimated experimental values, extracted from Gaussian fits of the data, are divided by 0.65 to take into account that only 65% of light is incident within $12.5\mu\text{m}$ of the beam center and the simulation values, also extracted from Gaussian fits (which include frequency depended elliptical mirror overfilling), are divided by 0.96 for consistency, as 96% of light lies within a radial distance of $12.5\mu\text{m}$ in the $20\mu\text{m}$ diameter Gaussian beam used in simulations. TE and TM results are blue and red respectively.

### 6.5.3 Comparison of Experimental and Simulation Absolute Bandwidth Results

The finite collection area of the elliptical mirror greatly affects the measured transmission bandwidth. Light diffracted out of a grating at a frequency away from the peak in-coupling frequency has a diffraction pattern centered away from the in-coupling angle, as is shown in figures 4.13a and 4.13b. This light is not centered on the elliptical mirror, and only a fraction of it is detected (this is effectively an angle dependent overfilling factor). The farther the excitation frequency is from the peak frequency, less light is collected, leading to narrowing of the measured transmission peak as compared to what it would be if all the out diffracted light was collected. The effective FWHM bandwidths of the experimental coupling spectra, corresponding to transmission from directly before the input grating to directly after the elliptical mirror, are compared to those simulated (with the frequency dependent overfilling fractions accounted for) in figure 6.14. The simulated and experimental effective
bandwidths agree reasonably well with TE bandwidths ranging from 58-77/cm (14-19nm) and TM bandwidths ranging from 114-141/cm (29-35nm).

6.5.4 Comparison to the Literature

In the literature, grating coupling efficiencies are commonly measured by single mode fibre-coupled light, with a 10µm beam diameter, incident near 10° to the vertical on an input grating which then couples light into a waveguide leading to an output grating. The light diffracted from the output grating is collected by a second fibre. The bandwidths and efficiencies depend on positioning of the fibres, which is precisely controlled to optimize the transmission. The in-coupling and out-coupling spectra are often estimated to be the same, and the single grating 3dB (roughly equal to FWHM) bandwidths and efficiencies are reported. Coupling efficiencies and bandwidths of fully-etched gratings reported in the literature are summarized in table 6.5.4.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Transmission (%)</th>
<th>FWHM (nm)</th>
<th>Pol.</th>
<th>Angle (°)</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halir(2009) [16]</td>
<td>25</td>
<td></td>
<td>TM</td>
<td>11</td>
<td>Rectangular lattice of rectangular holes with apodized sizes</td>
</tr>
<tr>
<td>Chen(2009) [10]</td>
<td>12</td>
<td>29</td>
<td>TE</td>
<td>8</td>
<td>2D rectangular lattice of circular holes</td>
</tr>
<tr>
<td>Liu(2010) [27]</td>
<td>17</td>
<td>35</td>
<td>TE</td>
<td>15</td>
<td>Photonic crystal holes repacing 1D “grooves”</td>
</tr>
<tr>
<td>Halir(2010) [17]</td>
<td>18</td>
<td>42</td>
<td>TM</td>
<td>12</td>
<td>Rectangular lattice of rectangular holes with apodized sizes</td>
</tr>
<tr>
<td>Antelius(2011) [3]</td>
<td>12</td>
<td>58</td>
<td>TE</td>
<td>10</td>
<td>Chirped 1D grooves</td>
</tr>
<tr>
<td>Antelius(2011) [3]</td>
<td>52</td>
<td>45a</td>
<td>TE</td>
<td>10</td>
<td>Chirped 1D grooves with optimized oxide thickness</td>
</tr>
<tr>
<td>Chen(2011) [11]</td>
<td>36</td>
<td>46a</td>
<td>TE/TM</td>
<td>15</td>
<td>Square lattice of rectangular holes with reflecting layer</td>
</tr>
<tr>
<td>This work†</td>
<td>2.3</td>
<td>2.5</td>
<td>TE</td>
<td>12</td>
<td>2D rectangular lattice of circular holes</td>
</tr>
<tr>
<td>This work†</td>
<td>7</td>
<td>13</td>
<td>TM</td>
<td>-19</td>
<td>2D rectangular lattice of circular holes</td>
</tr>
</tbody>
</table>

* Simulated bandwidth  
† 35%/4% incident power outside of grating region taken into account for exp./sim. efficiencies

Table 6.1: Summary of fibre-to-fibre transmission results for fully-etched designs (except the last two entries which are for the free-space experiments described in this thesis). Bandwidths are experimental FWHM, unless otherwise stated.
Single-grating experimental TE coupling efficiencies of 42%, 35% and 34% were reported by Liu et al [27], Antelius et al [3] and Chen et al [10] respectively. The input fibre to output fibre transmission coupling efficiencies are approximately 17%, 12% and 11% with FWHM bandwidths 48nm, 58nm and 29nm. These TE coupling efficiencies are over four times greater than those found in this thesis, even with the beam quality taken into account (as shown in table 6.5.4). The TE bandwidths in this thesis are also less than half of those found by Liu and Antelius. The experimental TM coupling efficiency and bandwidth in this work are estimated to be 7.3% and 30nm at 19° incidence, which are lower to those reported by Halir et al [17], 18% and 42nm.

These grating performance results depend not only on the grating structure, but also on the measurement techniques implemented, making it difficult to directly compare the results from the literature (where fiber excitation and collected is used), to those from this thesis (where excitation and collection are done in free-space). As is discussed in chapter 4, light diffracted from the output grating overfills the the elliptical collection mirror 15cm from the sample, even at the peak coupling frequency, when the output beam is centered on the mirror. In chapter 5, the elliptical mirror is experimentally found to collect 47% for S-polarized light incident at 11°, at its peak coupling frequency, and is found to collect between 57 – 65% for S and P-polarized light in simulations (chapter 4). This free-space collection scheme is less effective than a 10μm core fiber, aligned directly above the grating for collection, resulting in lower experimental coupling efficiencies. However, the elliptical mirror overfilling does not fully account for the low coupling efficiencies reported in this thesis, as multiplying the efficiencies by 2 still yields lower results than those reported in the literature. Part, but not all of the TE discrepancy, may be attributed to the higher in-coupling efficiency for 10μm versus 20μm spots, as was shown in figure 4.6a.

It is likely that the bandwidths in this work are smaller than those in the literature because i) the excitation spot used here is at least twice the size, ii) the grating coupling strengths reported are weaker and, primarily, iii) the elliptical mirror collects a smaller range of angles than an output fiber. As discussed in chap 2, i) and ii) imply slowly decaying grating modes over a large area which result in a bandwidth narrowing, whereas in iii) this
contribution to bandwidth narrowing is a function of the measurement technique.

To put these results in context with the gratings studied in this thesis, we note that for the more typically studied S/TE mode polarization, the peak in-coupling efficiency calculated for either 10 \( \mu \text{m} \) or 20 \( \mu \text{m} \) diameter Gaussian excitation beams is on order 21\% (see figures 4.5, 4.6, and 4.14). The total peak out-coupling efficiency, not taking into account the fact that only roughly half of the out-diffracted light is collected by the elliptical mirror, is also \( \sim 21\% \) (see figure 4.14). These simulation results for the S/TE polarization are in good agreement with the measurements, when the imperfect excitation spot shape and the aperture effect of the elliptical collection mirror are taken into account. The best values reported in the literature for different grating designs, as summarized in table 6.5.4, are from 50\% to 100\% higher than 21\%. For the less studied P/TM polarization, the theoretical and experimental peak coupling efficiencies are both higher than for the S/TE polarization in our gratings, roughly by a factor of two times, but the agreement between experiment and simulation is not as good as for the S/TE polarization. There is insufficient data in the literature to make valid comparisons with these results.

### 6.5.5 Control of the Grating Coupler Tuning Range

Many photonic devices are designed to operate near specific frequencies, so it is important that integrated I/O couplers can efficiently couple light of the appropriate frequencies into the photonic circuit. For example, to achieve maximum resonant cavity transmission through a device described in chapter 3 (gratings/waveguides/microcavity), the grating coupling peak must be centered around the resonance frequency of the cavity. For a given device, optimal coupling cannot always be achieved because the grating coupler spectrum can be tuned over only a finite range of frequencies, in part limited by the range of in-coupling and out-coupling angles attainable with the measurement set-up. Control of the grating coupling peak frequencies is desirable in integrated photonic circuits.

The TE and TM grating modes are tuned in energy by coating the silicon with a 2\( \mu \text{m} \) photoresist without making significant changes to the coupling performance (as shown in
figures 6.9 and 6.10). The TE coupling energies are increased by approximately 400cm$^{-1}$, while the increase is even greater for TM coupling. The shift to higher energy for the uncoated bands can be attributed to a greater concentration of the mode energy in air, rather than resist. This simple energy tuning method is used as a means of correcting fabrication errors, and has potential to offer another dimension of flexibility when designing grating input/output ports.

Another way to achieve the effect of coupling peak frequency tunability is to consider grating couplers with different hole sizes. Grating-to-grating transmission measurements were taken for five different resist-coated devices, with results in figures 6.8a and 6.8b. The peak frequencies are plotted as a function of hole diameter for S and P-polarized excitation at 11°, for resist covered samples, in figure 6.17. Gratings with larger hole sizes generally have higher maximum coupling frequencies, due to their greater field concentration in air, rather than the slab. The grating hole size variation causes less of a shift in the TM band than the TE band. Their maximum coupling efficiencies, bandwidths and integrated power generally follow similar trends, with similar performance levels, as shown in figures 6.10a to 6.10c.

![Figure 6.17: Peak frequencies for TE (red) and TM (blue) mode excitation at 11° excitation for resist coated samples as a function of the hole diameter of the gratings.](image)
Chapter 7

Resonant Cavity Transmission

Optical microcavities are useful in many integrated optical applications as they can trap photons of specified frequencies, in very small volumes, over many optical cycles. To be integrated into photonic circuits, the cavity modes can be coupled to waveguides that transfer light to and from the cavities. In the devices studied in this thesis, the input/output gratings couple light into and out of two waveguides symmetrically coupled to a photonic crystal microcavity. As mentioned previously, all elements of these devices (gratings, waveguides and photonic crystal) were fabricated using a single-etch process. In this section, successful measurements of the resonant cavity transmission of multiple devices are reported. The change in the transmission lineshape is compared before and after post-fabrication removal of the buried oxide layer below the photonic crystal cavity region.

These resonant cavity transmission measurements are also of interest for grating coupler characterization. Grating couplers are most commonly used to couple light between devices and optical fibres. Grating-to-grating transmission experiments do not provide an ideal basis for comparing free-space and fibre excitation efficiencies because the spot size of a fibre is approximately half that for free-space excitation, and light in the slab diverges more quickly, potentially overfilling the output grating. For a better comparison, resonant cavity transmission is measured for several devices using both free-space and fibre excitation methods with S-polarized light. These results, as well as the device transmission for back-coupled P-polarized incident light near the TE resonance frequency, are reported in this section.
7.1 Measurement Procedure

The transmission set-up in figure 5.1 is used to measure device transmission spectra. Both free-space and fibre excitation methods are used to send light towards the input grating. For the devices measured, only S-polarized incident light is found to resonantly excite the fundamental cavity mode of the L3 cavities. On resonance, light from the cavity is transmitted through the waveguides to the output grating while off resonance very little light is transmitted to the output grating. As light can only be faintly observed on the CCD camera over a very narrow bandwidth, the alignment procedure is more challenging than for grating-to-grating coupling. The first step is to determine the resonance frequency of the cavity, and then the grating coupling angle that centers the grating coupling peak at this frequency. This can be done by aligning the beam blindly on the input grating (without an output spot visible on the CCD camera to optimize) and measuring spectra for different coupling angles. However, this trial and error method can be very time consuming and is generally not effective, as the resonance peak will not be detected if the alignment is poor. To find the cavity resonance frequency more directly (without the use of the gratings and waveguides), resonance scattering measurements are made directly on the cavity, from the top half space. The resonance scattering experiment, described in [28], involves focussing polarized light on a cavity at normal incidence and collecting perpendicularly polarized light scattered off the sample. This cross polarization geometry is designed to eliminate directly reflected light, so that the spectral behavior of resonantly scattered light is detected. The set-up used is illustrated in figure 7.1a. The resulting spectra typically have a Fano line-shape around the resonance frequency with a frequency dependence,

\[
\frac{(ca + f - f_0)^2}{(f - f_0)^2 + a^2}
\]  

(7.1)

where \(c\) and \(a\) are constants and \(f_0\) is the resonance frequency. An example of a spectrum fitted by (7.1) and a second order background polynomial is shown in figure 7.1b, where the fit yields a resonance frequency of 6363cm\(^{-1}\). After extracting the resonance frequency from
Figure 7.1: a) Resonance Scattering set-up used for cavity resonance frequency measurement. b) Example spectrum fitted with Fano lineshape. The resonance frequency was found to be 6363/cm.

a fit, the appropriate coupling angle is chosen.

All beam alignment is carried out at the cavity resonance frequency. To optimize the beam focus for free-space excitation, the alignment procedure for grating-to-grating coupling, outlined in section 6.2, is followed. In this case, the beam is swept along the column of gratings adjacent to column of the input grating and the focus is optimized so that the beam fills only one grating at a time. For fibre excitation, the fibre is brought as close as possible to the sample without making contact. In both cases, the beam is then positioned by optimizing the output light seen on the CCD camera and the iris is closed around the out-coupled light. The detector is slid into place and the beam position is fine-tuned to maximize the signal.
For transmission efficiency calculations, the free-space and fibre reference measurements, described in sections 5.2 and 5.3, are taken.

7.2 Undercutting Effects

The free-space excitation transmission spectra, for device R4C5s3 on chip E8, is measured before and after undergoing undercutting, and are plotted together (with arbitrary scaling) in figure 7.2a. The black spectrum is for a device, as shown in figure 3.10. In this case, light is coupled into the cavity with oxide below, and air above, via the resist covered gratings. The peak is weak, and sits on top of a background signal, due to stray scattered light. The substrate is removed below the photonic crystal using the undercutting procedure outlined in section 3.3 and the transmission spectrum of the undercut device (blue) is plotted in figure 7.2a. Obviously the signal has increased considerably, as has the cavity Q factor.

There appears to be high frequency noise in the spectra in figure 7.2a, however, upon closer inspection, the “noise” has periodic behaviour characteristic of Fabry-Perot oscillations. The spectra are fit with Lorentzians modulated by Fabry-Perot oscillations (red) in figures 7.2b and 7.2c. The free spectral range (FSR) of the Fabry-Perot oscillations is approximately 4.4 cm$^{-1}$.

7.3 Free-Space and Fibre Excitation Comparison

The resonant cavity transmission using free-space and fibre geometries were measured for five different devices. The free space measurements have good reproducibility while the fibre measurements are very sensitive to the distance between the fibre and the sample, which is chosen by eye to be as small as possible without contact. The variation in the fibre coupling from attempt to attempt on the same grating is over 30%.

Resonant transmission efficiency comparisons for free-space (black) and fibre (red) excitation of five different devices are shown in figure 7.3: R5C5s5, R5C5s6, R4C5s1, R4C5s2 and R4C5s3 on chip F8, which take into account the 47% elliptical mirror overfilling. The
Figure 7.2: Transmission spectra of device R4C4s3 on chip E8 before (black) and after (blue) undergoing undercutting. A comparison of the plots is shown in a) while b) and c) show the pre and post undercutting spectra fitted with Lorentzians modulated by Fabry-Perot oscillations (red). The transmission peaks were at 6334.9 cm\(^{-1}\) and 6434.6 cm\(^{-1}\) with quality factors approximately 280 and 2860. The free spectral range of the Fabry-Perot oscillations was approximately 4.4 cm\(^{-1}\).

measurements of R4C5 and R5C5 were done with light incident at 13° and 16° respectively. The ratios of the maximum transmission efficiencies for fibre to free-space excitation are 0.47, 0.36, 0.94, 0.33 and 0.45 for the devices in figures 7.3a to 7.3e. No obvious trend is observed in comparing the transmission with free-space and fibre excitations. This is likely due to inconsistencies in the alignment procedure used for fibre excitation.

The resonant cavity transmission is also measured for numerous devices on chip E8 using free-space excitation (see Appendix). The resonance frequencies of the cavities measured range from 6329 cm\(^{-1}\) to 6567 cm\(^{-1}\), as shown in table 7.1. The quality factors of the cavities also vary, ranging from approximately 1300 to 5000. Both the peak energies and the quality
Figure 7.3: Comparison of transmission efficiency spectra using free-space (black) and fibre (red) excitation for devices a) R5C5s5 b) R5C5s6 c) R4C5s1 d) R4C5s2 e) R4C5s3. The raw data is divided by 0.47 to correct for overfilling of the elliptical mirror.

factors vary systematically with the 50nm shift in side holes adjacent to the L3 cavity (s1 no shift, s6 50nm shift).

### 7.4 TM Transmission Results

The transmission of P-polarized light through a waveguide/cavity device is measured for an incidence angle chosen to center the back-coupling grating peak frequency near the cavity TE resonance frequency. The transmission spectrum is compared to the grating-to-grating coupling spectrum in figure 7.4.
<table>
<thead>
<tr>
<th>Device Group</th>
<th>Frequency (cm$^{-1}$)</th>
<th>Quality Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s1</td>
<td>s6</td>
</tr>
<tr>
<td>R3C4</td>
<td>6356</td>
<td>6316</td>
</tr>
<tr>
<td>R3C5</td>
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<tr>
<td>R5C4</td>
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</tr>
<tr>
<td>R5C5</td>
<td>6567</td>
<td>6518</td>
</tr>
</tbody>
</table>

Table 7.1: Measured resonance frequencies and quality factors of devices on chip E8. The side holes adjacent to the L3 cavity are unshifted for “s1” devices, and are shifted by 50nm for “s6” devices.

Figure 7.4: Plot of device transmission efficiency spectrum (blue, right axis scaling) and the grating-to-grating spectrum (red, left axis scaling) for back-coupled P-polarized light incident at 10° on sample R3C5s2 on chip F8. The raw data is divided by 0.47, approximate overfilling of the elliptical mirror. The TE cavity resonance frequency at 6350 cm$^{-1}$ is indicated by the dashed line.

7.5 Discussion

7.5.1 Resonant Cavity Transmission

The resonant cavity transmission spectra of device R4C5s3 on chip E8, before and after undercutting agreed reasonably well with fits of Lorentzian functions modulated by Fabry-Perot oscillations, as plotted in figures 7.2b and 7.2c. Before undercutting, the resonant transmission peak is centered at 6334.9cm$^{-1}$, while after it is blue shifted to 6434.4cm$^{-1}$, as shown in figure 7.2a. This energy shift is due to the reduction in the index of refraction below the slab when the substrate is removed. The quality factor of the cavity also increases from approximately 280 to 2860, due to the increase in the index contrast at the bottom interface of the slab, allowing for better light confinement in the slab. In simulations of the
photonic crystal region of a similar device (R4C5s1), as outlined in [15], the cavity frequency is shifted by 54cm\(^{-1}\) after undercutting and the quality factor increases from 800 to 3300. These results agree reasonably well with those found experimentally for R4C5s3.

Light resonates in the undercut cavity for a longer lifetime than in the substrate based cavity, due to the reduction of the out-of-plane leakage, resulting in an increase in peak transmission power. This is qualitatively observed on the CCD camera, where the out-coupled light spot becomes brighter, and it is also reflected in the relative signal to noise in the two spectra of figure 7.2a.

For a wave propagating with an effective index of 2.8 (approximately the TE mode effective index in the tapered waveguide), the FSR extracted from the fit, 4.4cm\(^{-1}\), corresponds to reflections happening over a distance of 406\(\mu\)m, which is reasonably close to the total length of the waveguide sections, 307\(\mu\)m (300\(\mu\)m (tapered) + 4\(\mu\)m (single mode) + 3\(\mu\)m (photonic crystal)). This indicates that the grating and the photonic crystal cavity likely act as weak reflectors forming a Fabry-Perot cavity. Fabry-Perot oscillations are apparent in some of the grating-to-grating transmission measurements, with FSR values near 14cm\(^{-1}\) (like in figure 6.5), corresponding to a 127\(\mu\)m resonator length for a slab mode with an effective index of 2.8. This is close to the edge-to-edge grating separation (195\(\mu\)m), indicating that light reflects off the grating/slab interfaces, as expected for impedance mismatching between the grating and slab modes (as in figure 2.12).

Overall free-space maximum resonant cavity transmission efficiencies measured for five devices ranged from 0.11% to 0.20% (accounting for 47% mirror overfilling), as reported in table 7.2. Dividing the resonant cavity transmission data by grating-to-grating (through the slab) coupling efficiency, from chapter 6, the transmission of resonant light between the two grating couplers (from the end of one tapered waveguide, through the cavity, to the end of the other tapered waveguide) is found to be approximately 11%.

The resonant cavity transmission spectra for fibre excitation (10\(\mu\)m spot diameter) are measured and compared to free-space measurements (with approximately 20\(\mu\)m spot diameter). The background signal that the peaks sit above, is lower for fiber excitation because the fibre cladding blocks some of the light scattered off the sample surface, so it does not reach
Table 7.2: Summary of resonant cavity transmission results of undercut cavities on chip F8. The transmission data from directly before input grating to directly after the output grating are in the second column (raw data is divided by 0.47 to account for elliptical mirror overfilling). The maximum grating-to-grating coupling efficiencies (from chapter 6, also divided by 0.47 here for consistency) are in the third column. The grating-to-grating coupling efficiencies are divided from the raw transmission data to estimate the transmission between the gratings, from the end of one tapered waveguide, through the cavity, to the end of the other tapered waveguide.

<table>
<thead>
<tr>
<th>Device</th>
<th>Raw Transmission</th>
<th>Grating to Grating</th>
<th>Net Waveguide to Waveguide</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5C4s5</td>
<td>0.18</td>
<td>1.9</td>
<td>10</td>
</tr>
<tr>
<td>R5C4s6</td>
<td>0.20</td>
<td>1.9</td>
<td>11</td>
</tr>
<tr>
<td>R4C5s1</td>
<td>0.17</td>
<td>1.1</td>
<td>15</td>
</tr>
<tr>
<td>R4C5s2</td>
<td>0.12</td>
<td>1.1</td>
<td>11</td>
</tr>
<tr>
<td>R4C5s3</td>
<td>0.12</td>
<td>1.1</td>
<td>11</td>
</tr>
</tbody>
</table>

The resonance frequencies and quality factors measured for eight devices on chip E8 are reported in table 7.1. The hole size, lattice pitch, and shifting of the side holes adjacent to the L3 cavity (0nm for “s1”, 50nm for “s6”), all affect the cavity properties. The shift is introduced to increase the quality factors, as has been successfully done in the literature, [4]. In FDTD simulations of the photonic crystal regions of R4C5s1 and R4C56 (simulations outlined in [15]), the resonance frequencies are $6404^{-1}$ and $6374 cm^{-1}$ respectively, with quality factors 1700 and 3300. This compares well with the experimental results for R4C5s1 and R4C56, shown in table 7.1), where the resonance frequencies are $6448^{-1}$ and $6421^{-1}$ and quality factors are 1700 and 3200 respectively. The difference in the resonance frequencies for the R4C5s1 on E8 and F8 (as in figure 7.3c) is only $5 cm^{-1}$, and the quality factors differed by only 6%, which is evidence that the deep UV exposure changes little from row to row (in the same column) on the wafer.
7.5.2 TM Cavity Probing

The cavity transmission spectrum, for a device that is excited with P-polarized light at the TE cavity resonance frequency, has 0.38\% maximum transmission (with a 47\% elliptical mirror correction factor) and is shaped very much like the grating-to-grating coupling spectrum, as shown in figure 7.4. These findings indicate that TM light does not experience the band gap at these frequencies in the photonic crystal region. In other words, the TM mode propagates “right through” the TE band gap. This is fully consistent with band structure of the 1D photonic crystal in figure 4.3a (in chapter 4), where the lowest TM band spans the lowest order TE band gap. The simulated band structure of a hexagonal photonic crystal in GaAs ($\epsilon = 12.6$, hole radius/pitch = 0.3, thickness/pitch = 0.75) was also reported to have TM modes within the TE band gap [22]. Dividing the cavity transmission results by the grating-to-grating coupling results, approximately 4.5\% of light is transmitted from the beginning of the input tapered waveguide to the end of the output tapered waveguide. This is approximately three times less than the waveguide-to-waveguide TE resonant cavity transmission.

Still, this relatively high TM transmission in the vicinity the cavity resonance frequency has potential applications for non-resonantly pumping or probing the cavity region with vertically-oriented electric fields. One such application is where non-resonant TM light, launched into the waveguides, excites emitters (like quantum dots) in the cavity without resonantly exciting the cavity directly. The quantum dots then emit photons into the cavity mode and cavity coupled photoluminescence is coupled out of the photonic circuit via TE grating coupling, at a different angle and with an orthogonal polarization, than the out-coupled TM light.
Chapter 8

Conclusions and Future Work

8.1 Conclusions

The extensive device characterization done in this thesis reveals that huge quantities of non-trivial, reasonably high quality silicon photonic circuits may be successfully fabricated using CMOS-based single-layer processing. A transmission set-up was used to experimentally measure the input/output grating coupler performances, for multiple devices, under a range of conditions. The grating couplers studied exhibit both TE and TM coupling capabilities and perform at a level suitable for most applications of interest. The experimental and simulation results agreed well in most respects, however there was poor agreement between TM mode coupling efficiencies. The experimental maximum coupling efficiencies for TE slab mode excitation, near 15% (single grating), agree well with those found by FDTD simulations, but are approximately a half of the best reported in the literature using fibre coupling. The TM maximum coupling efficiency results, near 26%, are approximately 10% lower than those found in the simulations and around half of those the literature. The experimental and simulation bandwidths agree reasonably well, and are lower than those reported in the literature due mainly to the effect of free-space versus fibre coupling and collection techniques. Up to this point, there has been no experimental work presented in the literature on the characterization of one-step etch grating couplers for both TE and TM coupling. In the context of device fabrication using CMOS fabrication techniques, the
Resonant cavity transmissions were measured for several undercut devices on the same chip, for both free-space and fibre TE excitation. The resonant transmission efficiencies, from the beginning of the input tapered waveguide to the end of the output tapered waveguide, are near 11%. The microcavities are found to be promising candidates for optical confinement schemes, with quality factors up to 5000. Neither the Q factors, or the overall transmission values for these samples were optimized, so improved performance can be expected from more optimized structures.

The transmission of the TM modes through the photonic crystal cavity structures near the TE cavity resonance frequency, showed no resonant behaviour, with a broadband transmission efficiency of approximately 4.5% from the beginning of the input tapered waveguide to the end of the output tapered waveguide. This is consistent with calculations that suggest the TM photonic crystal bands completely overlap the TE photonic crystal band gap. This broadband transmission is therefore a measure of the coupling from one single mode silicon ridge waveguide to another, through 8µm of photonic crystal material that supports TM mode propagation (modified by the photonic crystal waveguide and cavity texture). This presents possible applications where TM light is used to efficiently and non-resonantly excite a TE mode microcavity with vertically-oriented electric fields.

This study of prototype silicon photonic circuits, reveals that variation in the feature sizes of device components on each chip, and across the wafer, offers the flexibility to choose from thousands of devices to find the ones suitable for a given application. Furthermore, since there are multiple chips with virtually identical properties, once the ideal structures are identified, various post-processing procedures can be applied to different such samples. This breadth of selection is not feasible using many “one-of” devices fabrication techniques and makes using CMOS based silicon photonics foundry services an appealing option.

Most significantly, this work demonstrates that although free-space excitation and collection optics limit the maximum per-grating efficiencies to roughly 12% (TE) and 21% (TM), in these samples, such experiments can be carried out reproducibly and are convenient for experiments where the chips have to be held in liquid or vacuum environments. Using higher
quality focusing optics to achieve a tighter spot on the grating, and using an elliptical mirror at the output with a larger collection area, the experimental efficiencies are expected to approximately double. Furthermore, the important influence of incident angle, grating hole size, and resist coatings on the tuning range of the grating couplers has been quantified.

8.2 Future Work

These silicon photonic circuit devices could potentially be used for applications including nonlinear optics, atom trapping and single photon sources, when integrated with nanoparticles like quantum dots. The key feature, that makes these devices attractive, is the efficient coupling of the cavity mode to single mode ridge waveguides. The overall input-taper-to-output-taper resonant transmission of $\sim 10\%$ measured here, on non-optimized samples with Q’s of $\sim 5000$ is very encouraging in this regard.

Additional FDTD simulations and analysis of the current devices are required to determine the effects causing discrepancies the simulated and experimental maximum TM coupling efficiencies. For the next device design, the photonic crystal waveguides and microcavities, could be optimized, using FDTD simulations, for improved Q values and resonant cavity transmissions. As the devices will be used for multiple applications, some of which include the use of non-resonant TM mode coupling, the cavities and the grating couplers should be optimized for both TE and TM coupling simultaneously. The design sought after would allow for efficient TE and TM coupling at the same frequency, however not necessarily at the same angle, unlike in polarization independent coupling studies.

There are also several improvements that could be made to the chip design. Within each of the current chips, the photonic crystal design parameters (i.e. pitch, hole diameters and side hole shift) are systematically varied from device to device, however, the grating couplers are designed to be the same for every device. This design leaves little room for error in the etching of the grating holes. On the current chips, the actual grating hole diameters are much larger than the design diameters, causing there to be no overlap between the range of coupling frequencies achievable with bare gratings (no resist coating) and the
microcavity resonance frequencies. A future chip design will have systematic variation in the grating coupler diameters allowing for the flexibility to choose between devices with identical photonic crystal regions, but different grating coupler hole diameters.

It would also be useful to include devices where the photonic crystal region is replaced by a single mode waveguide, directly connecting the tapered waveguides. A transmission measurement of one of these devices would be used as a reference in resonant cavity transmission experiments to isolate the waveguide and grating transmission efficiencies from the cavity transmission efficiencies.

For the applications currently explored in this lab, free-space excitation and collection geometries are required for transmission measurements done on samples in cryostats and in solution. The free-space transmission set-up will be improved by replacing the excitation optics (two lens system) by a one-to-one elliptical mirror. The one-to-one elliptical mirror will be used to accomplish the same task as the two lens system, that is, image the fibre output (one focal point) on the sample surface (the second focal point). However, the mirror will be precisely shaped to reduce aberrations like those previously introduced by the simple lenses, and will achromatically focus light from the fibre to a tight spot (closer to 10µm) on the grating.

For applications where high intensity light is required, like in nonlinear optics and atom trapping, it is important that losses upstream of the input grating are minimized. The input polarizer, which currently reduces the power by \( \sim 50\% \), will be replaced with a fibre polarization controller. This device will be used to efficiently stabilize and control the polarization of light emitted from the fibre.

The existing elliptical mirror could be replaced by one with a larger collection area to increase the maximum transmission efficiencies measured. Although currently only \( \sim 50\% \) of light diffracted from the grating is collected at best, it does not pose a significant concern, as it is downstream of the output grating, and it has no impact on the light in the devices.

With the knowledge gained from the characterization work done in this thesis, it will be possible to pursue a wide range of applications with optimized devices and improved measurement conditions.
Bibliography


Appendix: Resonant Cavity Transmissions

Figure 8.1: Resonance cavity transmission measurements of devices in column 4, chip E8: a) R3C4s1 b) R3C4s6 c) R4C4s1 d) R4C4s6 e) R5C4s1 f) R5C4s6.
Figure 8.2: Resonance cavity transmission measurements of devices in column 5, chip E8: a) R3C5s1 b) R3C5s6 c) R4C5s1 d) R4C5s6 e) R5C5s1 f) R5C5s6